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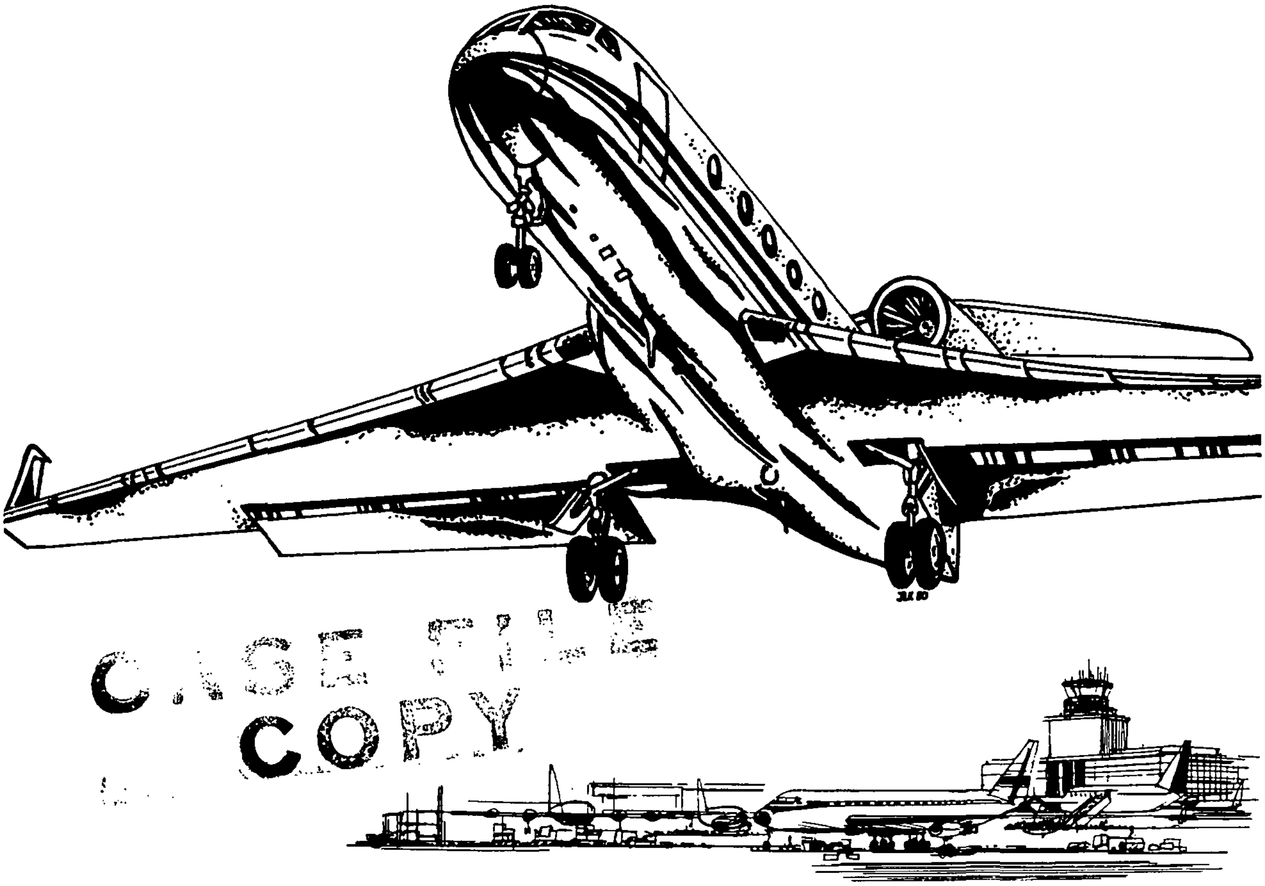

Risk to the Public From Carbon Fibers Released in Civil Aircraft Accidents

NASA SP-448

Risk to the Public From Carbon Fibers Released in Civil Aircraft Accidents

Prepared by

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Scientific and Technical Information Branch 1980
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Washington, DC

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PREFACE

This document constitutes the final report submitted by NASA to the Office of Science and Technology Policy, Executive Office of the President, and concludes the NASA portion of the Federal Government's carbon fiber study.

A coordinated Federal Government action plan was announced in January 1978 to study the potential problems arising from the projected increased use of carbon fiber composite materials in civilian applications. The primary concern was the electrical hazard associated with carbon fibers released from burning of carbon fiber composites. Such carbon fiber release might occur in crash fires of air or ground vehicles containing carbon composites and during disposal of carbon composite waste or worn-out parts. The Federal Government action plan outlined in NASA Technical Memorandum 78718, "Carbon Fiber Study" dated May 1978, assigned responsibility for various elements of the study to appropriate Federal agencies. Since NASA has been heavily involved in carbon-fiber-composite research and in the development of composites for use in civil aircraft, NASA was asked to quantify the risks associated with accidental release of carbon fibers from civil aircraft and to assess the need for protection of civil aircraft from accidentally released fibers.

Responsibility for the direction of the NASA study was assigned to the Graphite Fibers Risk Analysis Program Office, of the Langley Research Center. Program Manager was Robert J. Huston and Deputy Program Manager was Thomas Bartron. The technical elements of the program were directed by the following team members: Wolf Elber (dissemination and risk computations), Vernon L. Bell (fiber source), Richard A. Pride (demonstration testing), Arthur L. Newcomb (electronic instrumentation and testing), Israel Taback (vulnerability), Ansel J. Butterfield (industrial surveys), and Jerry L. Humble (aircraft system analysis). During the first year of the program, Karen R. Credeur was responsible for direction of the risk computation effort.

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EXECUTIVE SUMMARY

Because carbon fibers are strong, stiff, and lightweight, they are very attractive for use in composite structures. Since carbon fibers also have high electrical conductivity, free carbon fibers settling on electrical conductors can cause equipment malfunctions or damage. As long as the fibers are embedded in the matrix of a composite material, they pose no hazard. However, when the composite is burned, for example, in a crash fire, fibers can be released from the matrix, become airborne, and be disseminated over large areas; thus, the fibers may create a potential hazard to electrical and electronic equipment (fig. 1).

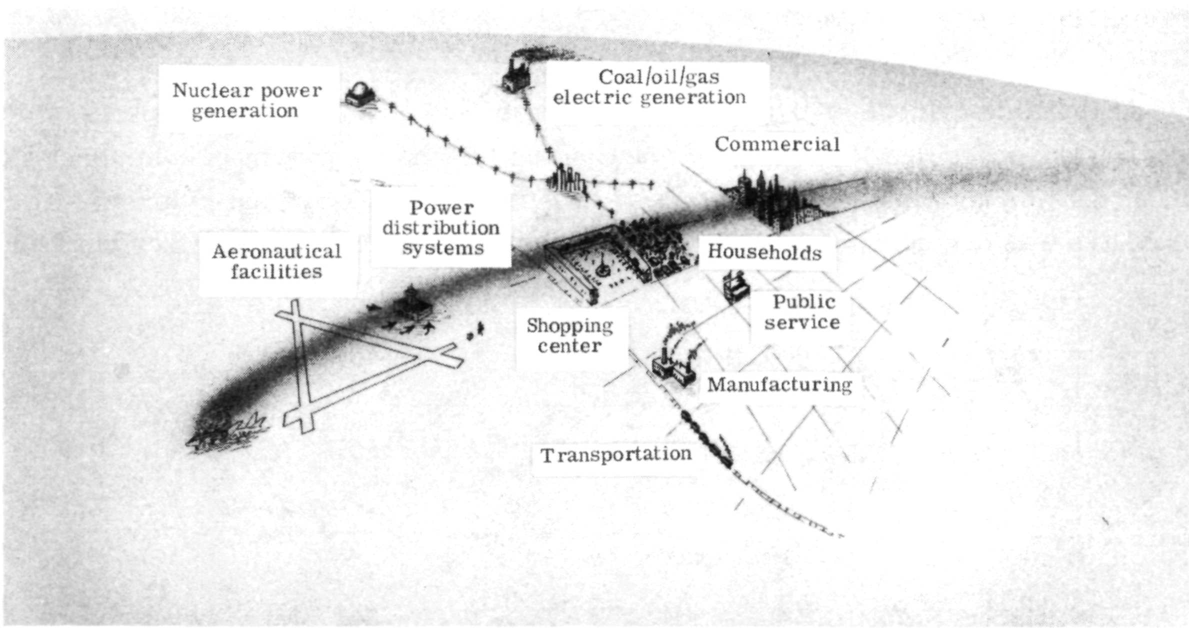

Figure 1.- The carbon fiber accident scenario.

Because future applications of carbon fiber composites were expected to increase in number, a Federal study of the potential hazard associated with widespread use of carbon fibers was initiated in 1977 under the direction of the Office of Science and Technology Policy, Executive Office of the President. Since NASA has been heavily involved in carbon-fiber-composite research and in the development of composites for use in civil aircraft, NASA was asked to quantify the risks associated with accidental release of carbon fibers from civil aircraft and to assess the need for protection of civil aircraft from accidentally released fibers. Responsibility for the direction of the NASA study was assigned to the Graphite Fibers Risk Analysis Program Office of the Langley Research Center. The program office initiated studies, gathered the necessary data to perform a

risk analysis, and developed a risk computation method in order to obtain the conclusions and findings of this report.

This document constitutes the final report submitted by NASA to the Office of Science and Technology Policy and concludes the NASA study. It highlights the relevant data gathered and the analyses performed by 19 government and contractor organizations involved with the program office in the risk assessment effort. The studies summarized herein resulted in the publication of more than 50 NASA Technical Memorandums, NASA Contractor Reports, and technical reports by other government agencies supporting the NASA risk assessment study. All of these documents are referenced for the convenience of readers wishing to study the procedures and data in more detail. The investigation included six major study areas. The findings for each are summarized in the following sections.

Fiber Source

At the time that the study was initiated, very few carbon composite parts of civil aircraft were scheduled for series production, but extensive growth in commercial aircraft usage was anticipated. Therefore, a two-part projection of the future use of carbon composites was developed (fig. 2). The first part for the commercial fleet was based on

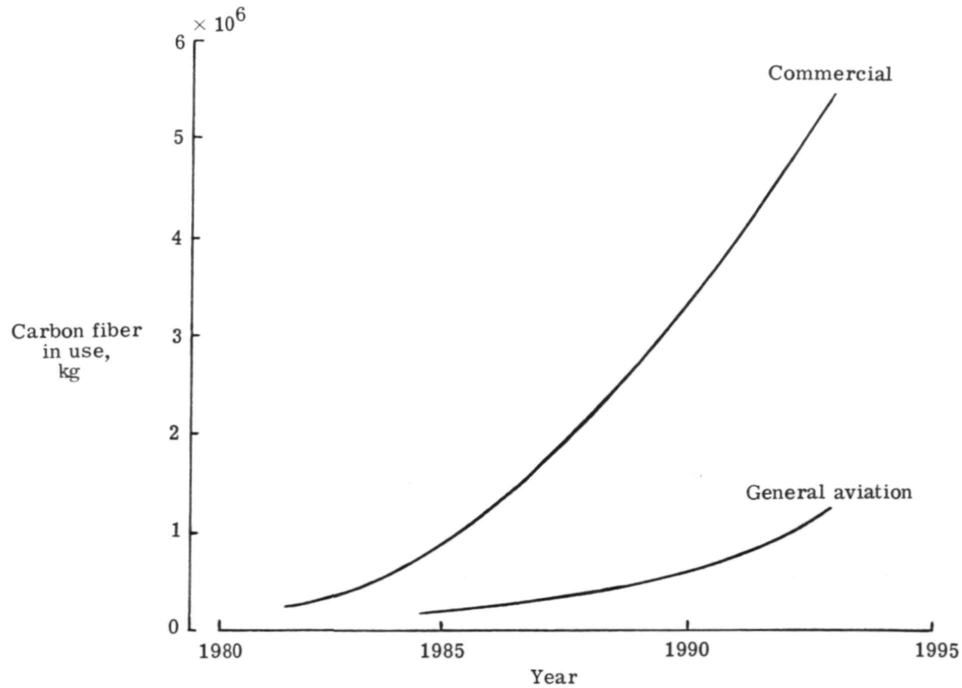

Figure 2.- Projected usage of carbon fiber in civil aircraft.

the plans and capabilities of the major commercial aircraft manufacturers in the United States and the Federal Aviation Administration study of the growth of the air-transport fleet over the next 15 years. By 1993, 73 percent of the commercial fleet were expected to contain some carbon composites. The second projection for general aviation aircraft, which includes the remainder of civil aircraft, assumed that carbon fiber usage would grow 30 percent per year from a base starting with one ongoing and two planned carbon fiber applications. This assumption led to an estimate that 25 percent of the general aviation aircraft would have some carbon composite structure by 1993.

From a projection of aircraft use of carbon composites, the amount of carbon composite involved in aircraft crash fires was estimated. National Transportation Safety Board (NTSB) records were analyzed and the consequence of accidents was assessed by a detailed review of company records by commercial airframe manufacturers. The annual rate of crash fire accidents with civil aircraft was assumed to remain constant in the future; that is, the effect of the expected expansion of the total civil fleet was assumed to be just balanced by improvements in safety.

The release of carbon fibers from burning carbon composites was quantified in nearly 300 experiments. The number of single fibers released was found to be relatively low, usually less than 1 percent of the fiber mass available in the consumed composite unless the burning debris was disturbed by explosive force. The released fibers were found to be relatively short, about 2 to 3 millimeters.

Fiber Transport

Carbon fibers released from burning composites are carried by the fire plume and dispersed downwind. The level of exposure to carbon fibers at any locality near an accident is a function of a number of atmospheric variables. For the risk analysis, existing dissemination models, which had been derived from those used by the Environmental Protection Agency, were found to be acceptable for defining carbon fiber dispersion from fires.

An airborne fiber is potentially capable of causing an electrical malfunction. However, no further hazard exists once the fiber is on the ground unless it is picked up by air currents and redisseminated in the atmosphere. A study of a site where carbon fibers had been deposited in substantial quantities 3 years earlier showed that less than 1 percent of the originally deposited fibers were redisseminated and that the redisseminated fibers were broken into shorter lengths. Because of these low redissemination rates, the small surface area in the country that is conducive to redissemination, and the low damage that can be done by short fibers, redissemination contributes very little to the potential risk. Therefore, in the risk analysis no redissemination was assumed.

Outdoor electrical equipment, such as power distribution lines, receives direct exposure to the disseminated carbon fibers. However, the exposure of enclosed equipment is very much lower because buildings and other enclosures provide effective filtration. For example, a carbon fiber cloud passing through a common window screen retains only one-tenth of its fibers. The actual interior exposure is usually one or two orders less than outdoor exposure because of fiber fallout and air circulation. The fiber filtration factors used in the risk assessment were based on data from filter tests, building surveys, and correlation with air-conditioning and electrical industry standards.

Vulnerability of Equipment and Shock Hazard

Tests have shown that carbon fibers can cause malfunctions and damage electrical and electronic equipment. To determine the vulnerability of representative equipment, approximately 150 individual items were tested. The items selected for the tests included household appliances, business and factory equipment, aircraft avionics, and generic electrical and electronic devices. Most items, including many items found in the home, were not damaged by exposure to carbon fibers. Some, particularly fan-cooled equipment and equipment with open electrical conductors, failed, but only at carbon fiber exposure levels that would rarely be expected to occur outdoors from the burning of an aircraft using carbon composites. For the broad range of equipment considered in the risk analysis, the level of vulnerability of a particular piece of equipment was assumed to be that found in the test program for equipment of generically similar construction and circuitry.

As part of the vulnerability testing, the potential for shock hazards in electrical equipment was examined. At extreme exposure levels, some household appliances, particularly toasters, were susceptible to carbon-fiber-induced short circuits to the external case. On the basis of the test data, the projected carbon fiber usage, and the accident rate projected for 1993, analysis indicated that less than one shock annually would result from released carbon fibers. The shock current would not be lethal because the fiber would burn out before a dangerous level was reached. Therefore, the potential shock hazard is not considered a threat to life and was not considered further in the risk analysis.

Detailed analyses have been made by three domestic commercial aircraft manufacturers to evaluate the susceptibility of the civil transport aircraft to carbon fibers released in aircraft fires. The analyses were based on avionics vulnerability test data, airflow inside the aircraft (for fiber transport analysis), and the various operational modes of the aircraft. The analysis showed that for aircraft on the ground at an airport exposed to a carbon composite crash fire, the avionics equipment failure rate from the carbon fibers would be 0.0003 percent of the current normal operational failure rate.

Aircraft in flight, or in the process of landing and taking off, are considered completely invulnerable to airborne carbon fibers. Because the number of expected failures from carbon fibers is so low and because the equipment is already redundant to meet current operational requirements, no specific protection from carbon fibers is required for civil aircraft avionics. Aircraft avionics systems of the future are anticipated to be even less vulnerable to carbon fibers than the current systems, because of the trends toward lower power systems with either coated circuit boards or totally enclosed cases.

Demonstration Tests

Two series of aircraft fuel fire tests were conducted which verified laboratory tests. Components of aircraft composite structure were burned in large outdoor jet-fuel pool fires to demonstrate the release and dissemination of fibers. The results indicated that less than 0.60 percent of the available carbon fiber was released into the atmosphere as single fibers. In pool-fire tests conducted in an enclosed facility, the amount of fibers released was less than 0.75 percent even when the burning composites were mechanically agitated. Exposure tests in this facility also demonstrated that the vulnerability of electronic equipment to fire-released fibers was predicted correctly by laboratory tests with virgin fibers.

Facility Surveys

Surveys were conducted to gather the data required to assess the economic impact of electrical incidents attributable to fire-released fibers. Over 60 public, utility, commercial, and industrial installations were visited to gather data on

- The sensitivity of life-critical or emergency services to airborne carbon fibers
- The sensitivity of commercial and industrial equipment to airborne carbon fibers
- The associated economic impact of fiber-induced failures

The surveys indicated that life-critical services, such as hospitals, were already protected against contamination. Their air-conditioning systems also provided isolation from airborne carbon fibers. For utilities, airborne carbon fibers would be expected to cause some failures in older equipment. In commercial institutions, exposure to carbon fibers would cause failures in working equipment, but computers containing critical records were adequately protected. Critical systems in many of the 21 industrial installations visited were equipped with high-efficiency filters or coated circuit boards that would provide effective protection against airborne carbon fibers. Continuous-process operations and assembly lines, where equipment failures could halt operations, had similar features adequate to protect against airborne carbon fibers. Most industrial

installations were able to shift operations or to work around electrical failures in equipment without major cost. Where equipment failures occur frequently, interchangeable spare parts were generally available. The results of these surveys were combined in the analysis models with census data to calculate the economic impact of carbon fiber accidents.

Risk Assessment

The primary objective of the risk analysis was to estimate the annual risk to the public resulting from the use of carbon composites in civil aircraft during 1993. A secondary purpose was to provide a framework for making decisions on composite material usage, material modification, and protection schemes. Two contractors independently developed methods for quantifying the potential cost of electrical equipment failures caused by airborne carbon fibers released from aircraft accidents. The analysis used data gathered in the NASA test program and incorporated the fiber release, fiber transport, and equipment vulnerability considerations previously described. This analysis concluded that the mean annual loss from commercial aircraft accidents was less than $1000, with the worst-case losses of $150 000 at probabilities of less than one chance in 2000 (fig. 3).

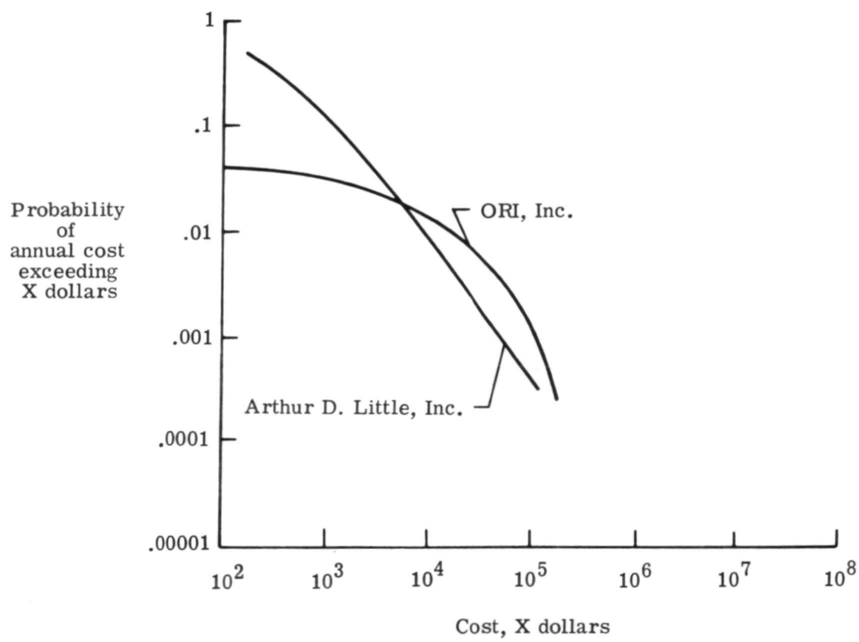

Figure 3.- 1993 national risk profile for carbon fiber released from commercial aircraft accidents. 1976 dollars; 1993 carbon fiber usage assumed.

An analysis of the general aviation fleet, including helicopters, showed that accidents with carbon fiber structural components will result in annual equipment damage of about $250 with only one chance in 10 000 of exceeding $110 000.

Along with the potential damage to equipment, the studies assessed the probability of power distribution outages. The analysis considered the effect of carbon fibers released from a worst-case aircraft accident scenario on outages experienced by individual electrical utility customers. One carbon-fiber-induced outage was expected to occur for every 200 000 to 1 000 000 outages currently caused by lightning, tree contact, vehicular damage, etc.; therefore, the risk of power outages is considered negligible.

Conclusions

The risk assessment described in this report indicated that carbon fibers accidentally released in an aircraft crash fire posed no threat to human life and that overall costs associated with carbon fiber release were extremely low. The following conclusions are drawn from these results:

- The risk of electrical or electronic failures due to carbon fibers should not prevent exploitation of carbon composites in aircraft.
- Additional protection of aircraft avionics to guard against carbon fibers is unnecessary.
- A program to develop alternate materials specifically to overcome the potential electrical hazard is not justified.

INTRODUCTION

The use of high-performance composite structures in aerospace vehicles is anticipated to increase significantly in the next few years. Most of the technical obstacles to successful application of carbon composites have been overcome, and several of their advantages (light weight, high strength, and high stiffness) are prompting increased consideration and application. However, laboratory tests and the accidental release of long free fibers from a carbon fiber plant caused concern that the properties of carbon fibers could have significant adverse economic impact (ref. 1). Since carbon fibers are electrically conductive, lightweight, and small in diameter, they could damage electrical and electronic equipment if released in the atmosphere. For example, fibers released in an aircraft crash fire may become airborne, be transported by the wind over a large area, and potentially damage equipment belonging to a large segment of the population.

This possibility was recognized by the Government, and in July 1977, the Director of the Office of Science and Technology Policy was directed by the President to conduct a study of the potential problems associated with the use of carbon fibers and to provide a plan for possible Federal action. The study (ref. 1) revealed that in addition to major growth in the use of carbon fibers in military and civilian aircraft, a significant amount is used in consumer products (e.g., skis, fishing rods, and golf clubs) and the amount used in automobiles is likely to soar. Worldwide use of carbon fiber is expected to grow from less than 0.5 million kilograms in 1977 to 0.5 billion kilograms by 1990.

Based on the study results, a national program on carbon fiber effects was established and announced in 1978 (ref. 1). Responsibility for elements of the program was delegated to the nine agencies listed in table I. The agencies initiated a variety of efforts to meet the goals set out in the national program on carbon fibers. Status reports on some of these studies and activities were presented at conferences (refs. 2 to 4). NASA-sponsored studies on alternative materials were described in a workshop reported in reference 5.

The NASA Langley Research Center (LaRC) was responsible for quantifying the public risk associated with the accidental release of carbon fibers from civil aircraft and for assessing the need for protection of civil aircraft systems from such fibers. Responsibility for the direction of the NASA LaRC study was assigned to the Graphite Fibers Risk Analysis Program Office. The Program Office sponsored and coordinated 19 studies conducted by NASA centers, private contractors, and other government

TABLE I.- AGENCIES PARTICIPATING IN NATIONAL PROGRAM AND THEIR RESPONSIBILITIES

Office of Science and Technology Policy (OSTP)	
	Program direction
National Aeronautics and Space Administration (NASA)	
	Risk assessment for civil aircraft accidents
	Protection measures for commercial aircraft
	Alternate and modified materials
	Management support to OSTP
Department of Transportation (DOT)	
	Risk assessment for surface transportation accidents
	Protection measures for surface transportation equipment
	Aircraft accident reporting
Department of Energy (DOE)	
	Power generation vulnerability and protection
	Power transmission vulnerability and protection
Department of Commerce (DOC)	
	Communication and computer vulnerability and protection
	Household equipment vulnerability and protection
	Carbon fiber market, production, and cost analysis
Environmental Protection Agency (EPA)	
	Environmental and industrial monitoring for carbon fiber
	Carbon fiber disposal methods
Department of Health, Education and Welfare (Now the Department of Health and Human Services, DHHS)	
	Environmental health analysis
Department of Labor (DOL)	
	Industrial worker safety standards
Defense Civil Preparedness Agency (Now the Federal Emergency Management Agency, FEMA)	
	Emergency procedures
	Carbon fiber incident analysis

agencies listed in table II. The results of these studies are reported in over 50 NASA Technical Memorandums, NASA Contractor Reports, and reports by other agencies. This report summarizes these results and cites the supporting documents.

TABLE II.- PARTICIPANTS IN NASA LaRC PROGRAM

Air Force Geophysics Laboratory

Fiber source test operations

AVCO Corporation

Fiber source

Bionetics Corporation

Fiber source
Fiber transfer
Equipment vulnerability

Boeing Commercial Airplane Company

Fiber source
Aircraft vulnerability

Douglas Aircraft Company

Fiber source
Aircraft vulnerability

The George Washington University

Statistical analysis

Jet Propulsion Laboratory

Instrumentation

Arthur D. Little, Inc.

Risk analysis

Lockheed California Company

Fiber source
Aircraft vulnerability

NASA Ames Research Center

Fiber source
Fiber dissemination

NASA White Sands Test Facility

Fiber source

National Bureau of Standards

Equipment vulnerability

ORI, Inc.

Risk analysis

Science Applications, Inc.

Fiber dissemination

TRW, Inc.

Fiber source

U.S. Army Ballistics Research Laboratory, Aberdeen, MD

Equipment vulnerability
Fiber transfer

U.S. Army Dugway Proving Ground

Fiber source
Fiber dissemination

U.S. Naval Surface Weapons Center Dahlgren, VA

Fiber source

These NASA studies were focused in the following areas, each of which is covered in a separate section of this report:

- Fiber Source
- Fiber Transport
- Vulnerability of Equipment and Shock Hazard
- Facility Surveys
- Risk Assessment

Included within "Fiber Source" are the necessary projections of future use of carbon fiber in aircraft and the character and amount of fiber released in the burning of carbon composites. "Fiber Transport" describes the dissemination of fibers from the burning composite, the possible atmospheric redissemination from the ground after deposition, and the penetration of building and electrical enclosures. "Vulnerability of Equipment and Shock Hazard" presents the sensitivity of equipment to carbon fiber from the standpoint of both equipment failure and potential shock hazard to individuals. "Facility Surveys" were performed to gather data required to bridge between laboratory and field experiments and the economic impact of electrical incidents attributable to fire-released fibers. "Risk Assessment" includes the development of suitable statistical approaches as well as appropriate evaluation of the sensitivities and implications of the various assumptions required.

FIBER SOURCE

An important element of carbon fiber risk assessment is the prediction of carbon fiber release from the crash and subsequent burning of commercial aircraft having structural parts made of carbon fiber composites. At the start of this investigation, no useful information on carbon fiber release was available from actual aircraft crash experience. However, the crash and burning of military aircraft with boron-epoxy parts and with carbon composite parts had generated free boron and carbon fibers. Thus the potential for carbon fiber release had been qualitatively demonstrated. Consequently, an extensive testing study was begun to provide experimental data needed to predict the amounts and characteristics of carbon fibers released from burning composites. The extent to which carbon fiber might be used in the structures of civil aircraft and be involved in fires by 1993 was also estimated.

Characteristics of Composites

Structural composite materials are generally multi-ply laminates of fibers embedded in a polymeric matrix material. Individual plies are cut to prescribed dimensions from tapes or broad goods and assembled with each ply oriented in the desired direction to provide specific strength and stiffness properties. The multi-ply laminate is cured by exposure to elevated temperature and pressure to produce a finished composite structure which has significant advantages over aluminum structure in terms of strength, stiffness, and weight.

Carbon fiber characteristics.- Carbon-based fibers, interchangeably referred to as graphite or carbon fibers, have high strength and stiffness that make them very attractive as the fibrous component of a composite material. Families of carbon fibers have been produced from a variety of precursor materials such as rayon, polyacrylonitrile, and

pitch. Moduli of elasticity of carbon fibers within these families range from 207 to 690 gigapascals (30 to 100 $\times 10^6$ pounds per square inch) depending on processing parameters and precursor. In general, the higher modulus fibers have lower electrical resistance as shown in figure 4. Both trends are attributable to the higher degree of

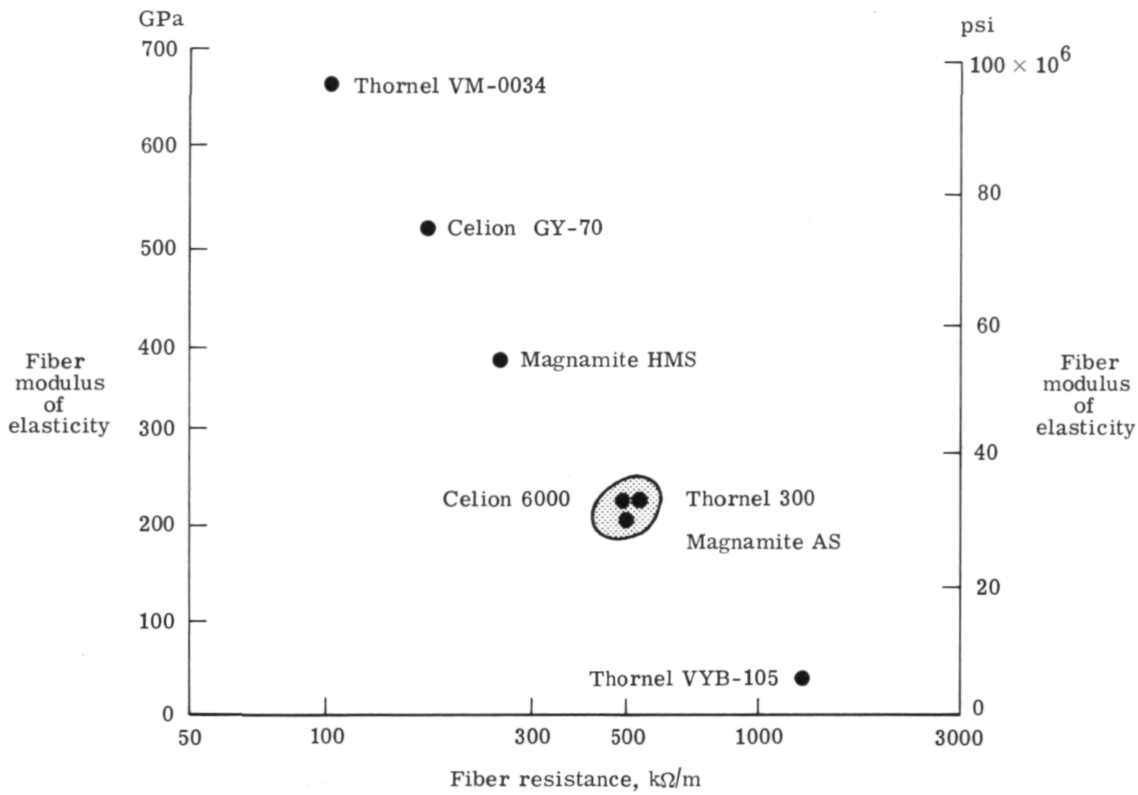

Figure 4.- Relationship between modulus of elasticity and electrical resistance of carbon fibers.

graphitization in these fibers during processing. Requirements for strength and damage tolerance in aircraft structures have led to the use of Thornel[1] 300, Magnamite[2] AS, and Celion[3] 6000 carbon fibers shown in the shaded area of the figure.

Matrix characteristics.- Structural composite material consists of fibers embedded in a matrix material. Although there are a variety of matrix materials for specific applications, epoxy matrices are commonly used in aircraft structural composites. Epoxies are highly cross-linked, high-molecular-weight, organic polymers that are generally cured at temperatures up to 475 K. They are not generally used where service temperatures exceed 360 K.

[1]Thornel: trademark of Union Carbide Corp.

[2]Magnamite: trademark of Hercules, Inc.

[3]Celion: trademark of Celanese Corp.

Epoxies exposed to temperatures from 1200 to 1300 K associated with aircraft accident fires are nearly consumed in a few minutes. Although new polymers are being sought which have improved mechanical damage tolerance, environmental resistance, and manufacturing processibility, no organic polymer is expected to survive temperatures of jet-fuel fires.

Composite Usage Projections on Civil Aircraft

The number of applications of composite materials is increasing because of their superior structural performance. The current and projected applications include sporting goods, industrial equipment, automobiles, aircraft, and spacecraft. NASA has conducted and sponsored extensive research and development of composite materials applied to civil aircraft structures. Three major airframe manufacturers have produced components, evaluated them in service (ref. 6), and studied designs with 100 percent carbon composite wings and fuselages. Recently, one manufacturer decided to produce most control surfaces, fairings, and engine nacelles with carbon composites in the next generation of commercial airplanes (ref. 6).

The manufacturers of commercial aircraft calculated the weight of carbon composite currently envisaged for each aircraft series to be built through 1993. This information along with manufacturer and Federal Aviation Administration estimates of fleet size, fleet mix, and airplane retirements was used to predict the distribution of carbon composite on the fleet of commercial airplanes in 1993. Figure 5 is a graphic representation of these

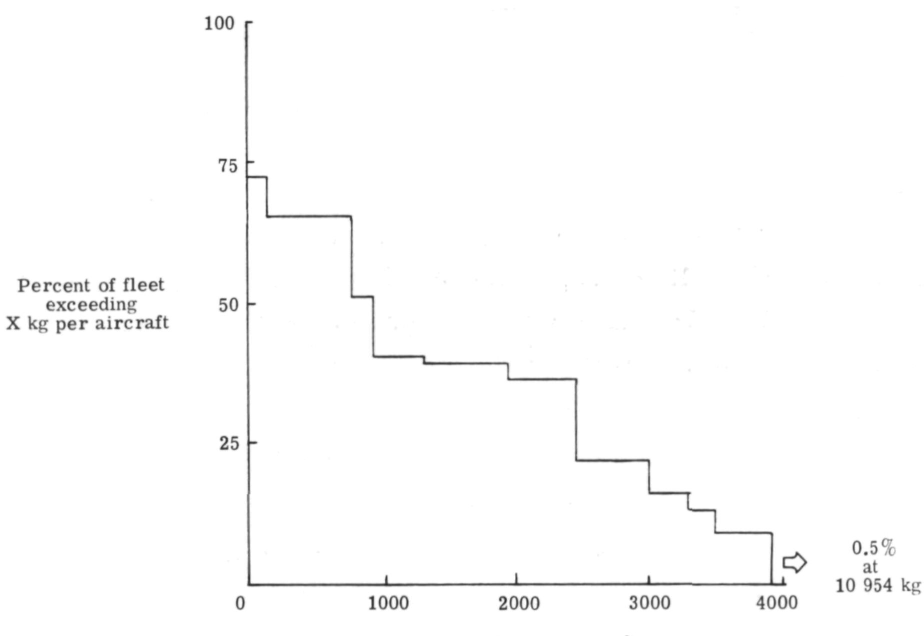

Figure 5.- 1993 projection of carbon fiber usage in commercial fleet.

data. In 1993, about 73 percent of commercial aircraft are expected to carry at least some carbon composites and 0.5 percent of the fleet to carry as much as 10 954 kilograms of carbon fiber per aircraft. This represents up to 10 percent of the airframe mass.

Figure 6 projects the amount of carbon fiber in service for commercial and general aviation aircraft from 1980 through 1993. The projection for commercial transport

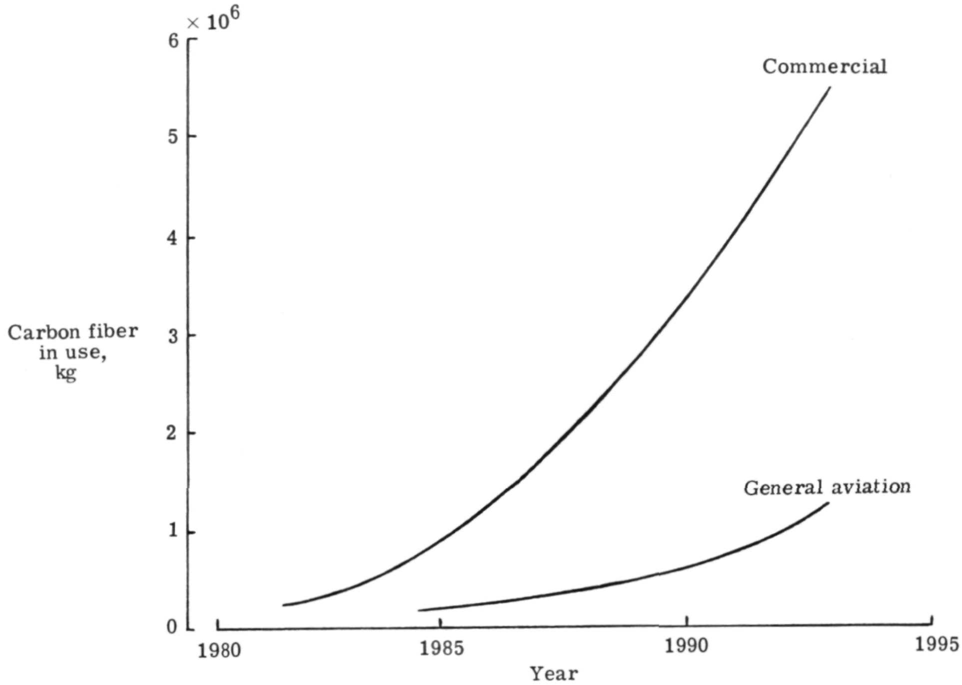

Figure 6.- Projected usage of carbon fibers in civil aircraft.

aircraft is based on data similar to those shown in figure 5 combined with fleet size. The projection for general aviation aircraft (which includes all other fixed and rotary wing aircraft) was based on 1978 usage increased at the rate (30 percent) projected for commercial aircraft. In 1978, there were one ongoing and two planned carbon fiber applications to general aviation aircraft.

Crash Fire Environment

Commercial aircraft accident records compiled by the National Transportation Safety Board and by manufacturers were analyzed (refs. 7 and 8) to determine the extent of fire damage to jet transports which have been involved in crashes since jets were first introduced. The results of the study provided the relationships among such critical aspects of crash fires as the phase of the aircraft operation, the percentage of structural

components involved in the fire, and the amount of fire damage. The frequency and extent of component fire damage in accidents with fires, shown in figure 7, are typical of data

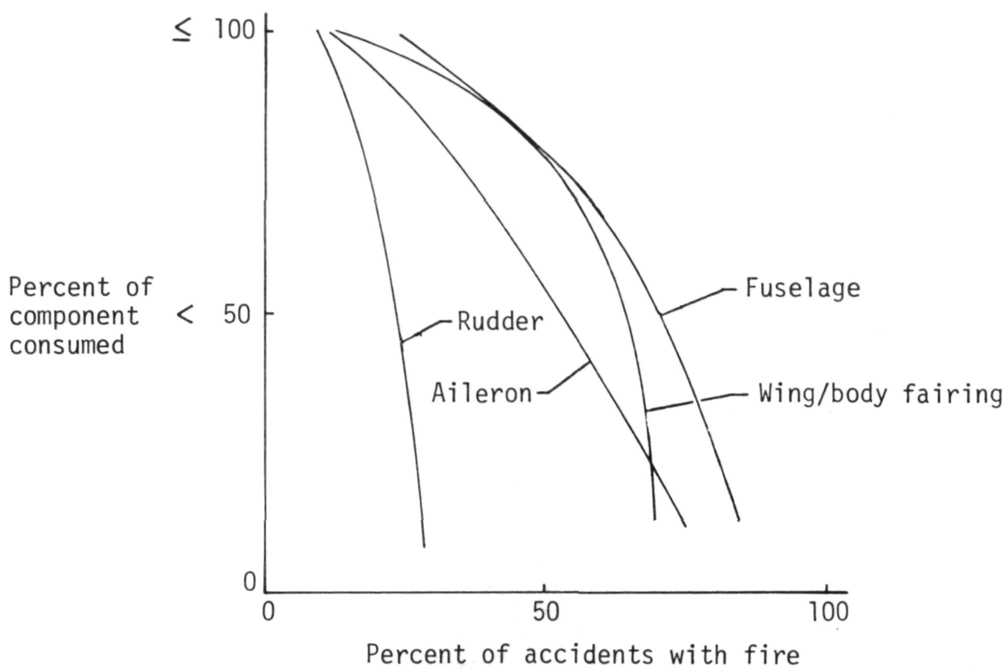

Figure 7.- Frequency and extent of fire damage to four aircraft components.

gathered in the study. For example, the rudder tends to be the least damaged component, while the fuselage is usually the most extensively damaged. The extent of damage by fire to composite parts was assumed to be equal to damage to the aluminum alloy parts covered in this study. Further, the expected expansion of the total civil fleet was assumed to be just balanced by improvements in safety. Thus, the number of fire accidents and the structural mass lost annually by fire were assumed to be constant. Commercial aircraft crash fires are sometimes accompanied by explosions, and this effect was also evaluated. Calculations based on these assumptions determined the amount of carbon fiber composite burned and, thus, the amount of fiber released from the simulated accidents upon which the risk assessments were based.

Fiber-Release Tests

Improved knowledge of the fire environment was essential to predict the fire temperatures, air and fuel concentrations, and flame velocities. These quantities were useful for making estimates of quantities and rates of matrix resin consumption, the amount of carbon fiber oxidation, and the amount and character of carbon fibers released into the atmosphere.

Composite material was deliberately burned and the products were analyzed to determine the number and sizes of released carbon fibers. Nearly 300 of these tests were conducted at several locations and ranged from small laboratory experiments (ref. 9) to large-scale outdoor simulations (refs. 10 and 11).

Combustion studies.- A set of preliminary fire and fire-plume calculations were made based on the best models and data available at that time. Atmospheric parameters, fire sizes, and fuel quantities were covered by the calculations. The study led to understanding the uncertainties of the models. The uncertainties then formed the basis for a series of outdoor tests (ref. 12) and further analyses (refs. 13 and 14) to better characterize combustion dynamics. The experimental tests involved outdoor JP-4 jet-fuel pool fires (fig. 8). Instruments on overhead cables measured temperatures, flame velocities, and gas species in the fires. The data from these fire tests were useful for refining the mathematical models (ref. 15) which guided the design of tests in which composites were burned.

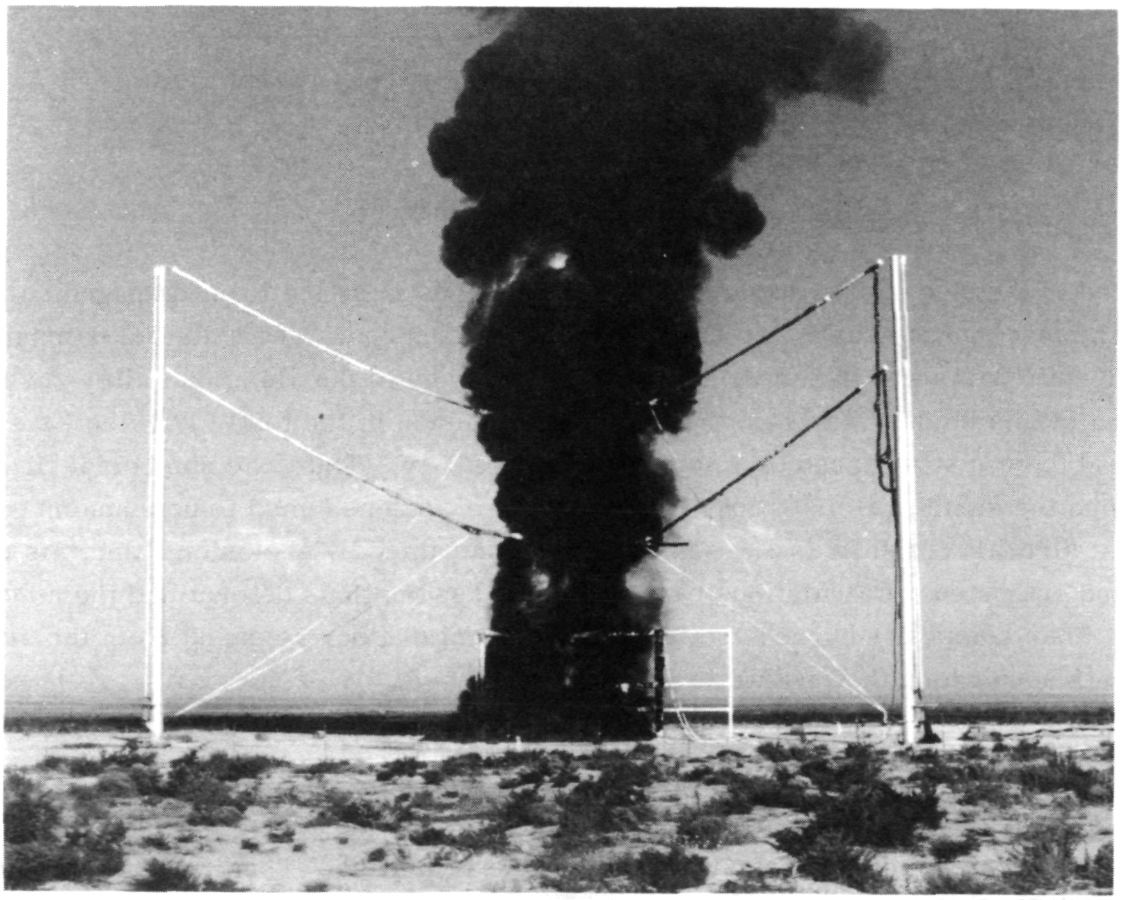

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Figure 8.- Jet-fuel pool-fire test.

Laboratory fiber-release tests.- The laboratory fiber-release tests (refs. 16 to 20) were conducted in closed chambers. Small samples (up to 0.1 square meter in area) of composite materials were burned with a gas burner. The test samples were generally either flat composite plates or small specimens cut from prototype composite aircraft structural components. A variety of disturbances – air currents, compressed gas blasts, mechanical impacts, or small explosions – were applied to the fibrous residue after the matrix had burned.

This portion of the carbon-fiber-source study concentrated on observing and characterizing single carbon fibers released during fire tests. Because of their buoyancy, single fibers were expected to be disseminated most widely, to readily penetrate the filters and cases of electrical and electronic equipment, to damage more equipment, and, thus, cause greater economic loss than would larger fragments. Electrical vulnerability experiments, discussed later, indicated that fibers less than 1 millimeter in length would not contribute significantly to the electrical problem. Accordingly, most of the fiber-release data gathered were for single fibers over 1 millimeter in length.

Most single-fiber data were gathered from rectangular sheets of clear adhesive-coated plastic film onto which fire-released fibers settled as they fell in the vicinity of the fire tests. The individual fibers on the adhesive film were then laboriously measured and counted by various optical microscopic techniques (refs. 21 and 22). As the risk analysis program progressed, special techniques and instruments (refs. 23, 24, and 25) were developed to automate or otherwise simplify the fiber-counting procedure.

The laboratory tests addressed the effects of the following variables on the amount and characteristics of carbon fibers released from burned composites:

Nature of fire (fuel-rich, fuel-poor)

Duration of fire

Disturbances to residue during and after fire

Composite thickness and configuration (cross-ply, woven, unidirectional)

Composite surface and edge effects

Types of composite materials (fibers, resins)

Composite quality

Large-scale aviation jet-fuel fire tests.- The tests previously described were all conducted with propane or natural gas as the fuel in order to provide a clean atmosphere and avoid excessive contamination of the laboratory test chambers. However, uncertainties remained as to how representative the carbon fibers were of those which would be released in a jet-fuel fire resulting from an aircraft accident. Also, equipment

vulnerability assessments made with mechanically chopped, unburned virgin carbon fiber required verification by equipment exposure to carbon fibers released in a jet-fuel fire. Therefore, two types of jet-fuel fire tests were developed to characterize fiber release from representative crash fires and to expose equipment to such fibers. In one type, the effluent from carbon fiber composite burned in a jet-fuel fire was ducted through a long, large-diameter tube past a group of operating electronic units. In other tests, carbon-fiber-composite aircraft components were burned in a fire above the surface of a large outdoor pool of jet fuel with various types of instrumentation overhead and downwind to sample the effluent and its fallout to determine fiber-release characteristics.

A part of a large steel shock-tube structure (fig. 9) was modified to burn carbon fiber composites in a jet-fuel fire (ref. 11). The fire was ignited inside the tube midway

U.S. Navy photograph

Figure 9.- Shock-tube fire test facility.

along its length. The fire-released fibers, combustion products, and heated air were transported approximately 270 meters through the tube by exhaust fans installed in the large end. Samplers monitored quantities and sizes of carbon fibers released by the fire. Electronic equipment was exposed in the tube near the exhaust end.

Outdoor pool-fire tests were conducted (refs. 3, 10, 26, 27, and 28) in which composite structural parts having aggregate masses of 45 kilograms or more per test were burned. Pool diameter (10.7 meters) and length of burn (20 minutes) were chosen to simulate a representative aircraft fire. Tests were conducted when weather conditions and wind directions ensured maximum likelihood of accumulating the desired data. The efflux of carbon fibers was monitored in several ways. Fibers were collected just above the flames by an overhead array of samplers (ref. 29) and about 60 meters downwind by a vertical array. A huge Jacob's ladder (305 meters square) was supported by two barrage balloons about 140 meters downwind of the fire (fig. 10). It supported numerous samplers

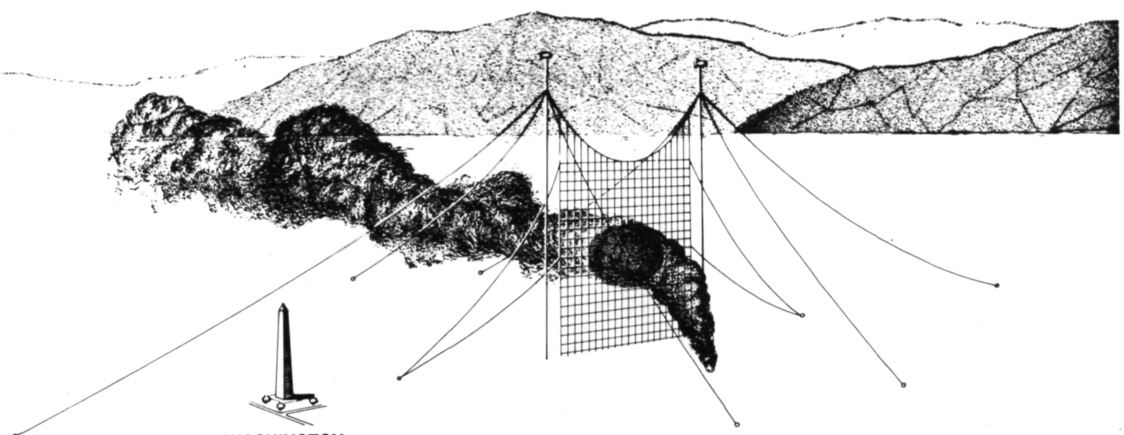


Figure 10.- Balloon-supported Jacob's-ladder net for sampling the fire plume.

to monitor quantities and sizes of fibers. Over 1300 passive samplers were mounted about 0.5 meter above ground in a fan-shaped array extending 19 kilometers downwind of the fire to measure fiber dissemination (refs. 28 and 30). In addition, strips and larger fragments released and deposited as far as 1 kilometer from the fire were collected by search teams and weighed for mass-balance accounting.

Results

The most important results of these experimental and analytical studies are summarized on the following pages. The supporting references document details of the tests and additional results.

Classification of debris.- In almost all tests, fibers were found with characteristics depicted in figure 11. Of special interest to this study were single fibers whose low fall

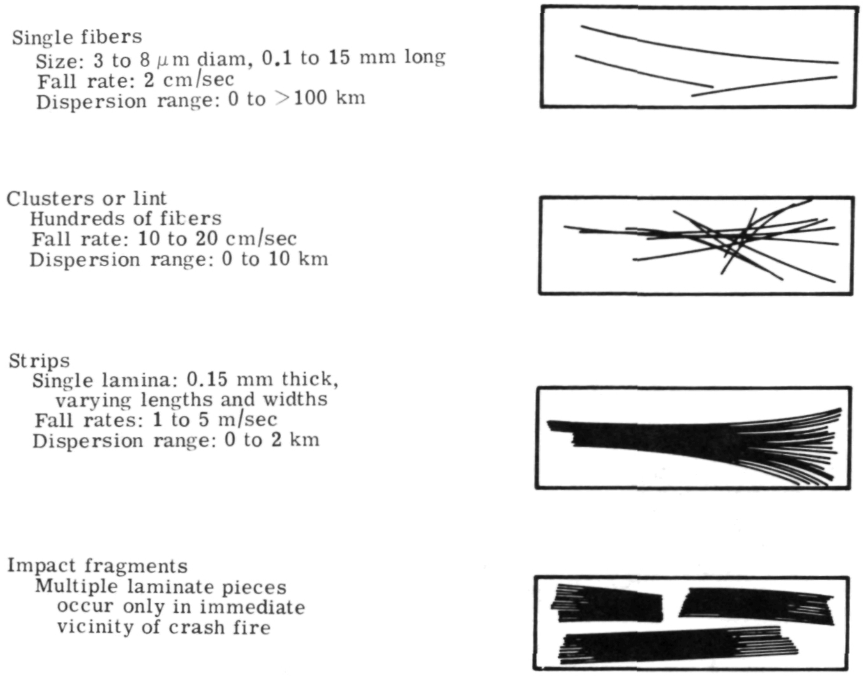


Figure 11.- Airborne fire-released carbon fibers.

velocity led to their dispersion over broad areas. Groups of fibers loosely bound in clusters fell faster and were dispersed over smaller areas. One-lamina-thick strips of fibers, bound together by incompletely burned resin or by the char formed when resin burned, were dispersed over even smaller areas. Still larger fragments, varying in size and shape, were usually produced only when the burning or burnt debris was mechanically disturbed. Because of their mass, they were rarely found beyond the immediate vicinity of the fire.

A fifth category of residue is shown in figure 12. The debris in the photograph was left after a 20-minute outdoor burn of stabilizers from a fighter aircraft. A large part of the structure remained in an identifiable shape in spite of major delaminations, oxidation of most matrix resin, and the release of fibers. In the foreground are a large number of strips described earlier. (The expanded wire mesh on which the man is standing was the test stand that had supported the stabilizers about 2 meters above the ground but had collapsed during the fire.)

U.S. Army photograph

Figure 12.- Carbon fiber residue from burned aircraft stabilizers.

Mass balance.- To the extent possible, debris of all these forms was statistically sampled, gathered, weighed, and summed to account for all fiber present in the experiment. Typical results from jet-fuel fire tests (refs. 10, 11, 26, 27, 28, and 31) are shown in figure 13. Between 15 and 60 percent of the original mass remained in place after the fire, except for the test in the shock tube. In the shock-tube test, the composite was burned in a wire basket that rotated about a horizontal axis to tumble the parts until all residue had been dispersed. Identifiable strips or fragments accounted for a significant portion of the original mass in many of the tests. The fiber samplers employed in these tests were designed and positioned to give a statistically reliable estimate of the single fibers (longer than 1 millimeter) released. For purposes of this calculation, only the lengths of fibers were considered; no mass adjustment was made for carbon consumed from the surface of counted fibers. Even so, single fibers accounted for only 0.2 to 0.6 percent of the fiber originally available (0.14 to 0.42 percent of original composite mass) except for the shock-tube test where single fibers accounted for 0.75 percent of the fiber originally available. The mass of fiber clumps was approximately equal to that of the single fibers. This left between 40 and 80 percent of the original mass not specifically accounted for. Of the 40 to 80 percent, most of the epoxy matrix was

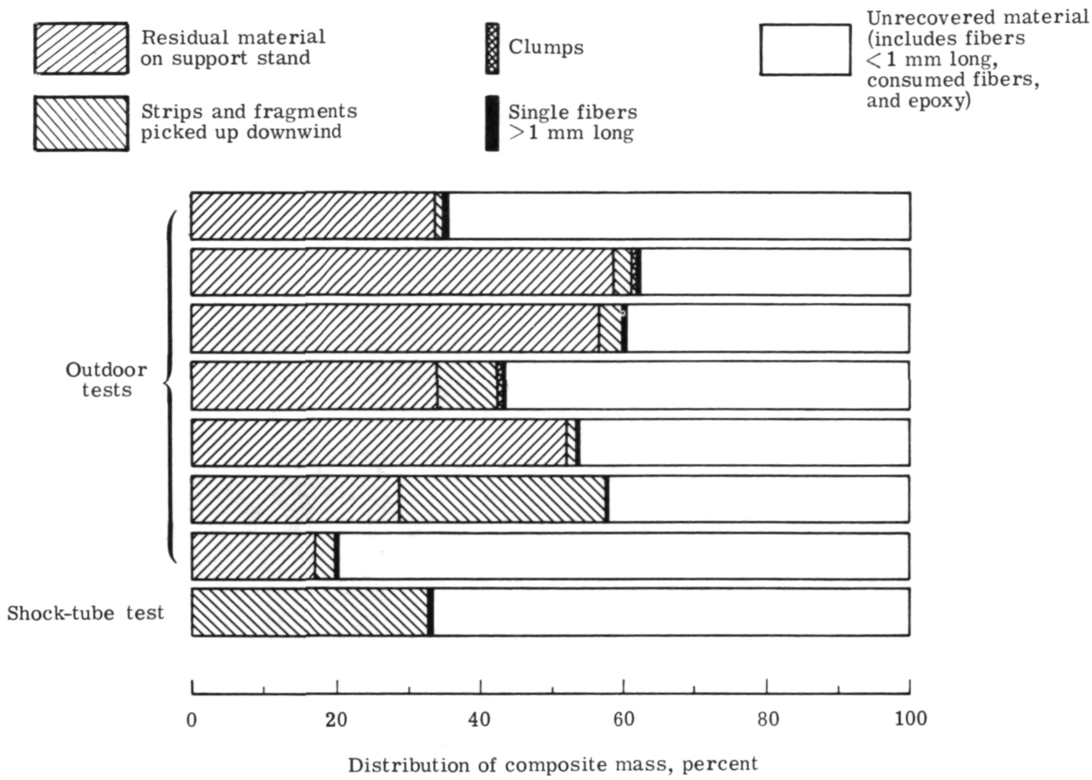


Figure 13.- Mass balance analysis of the composite materials burned in aviation jet-fuel fire tests.

consumed by oxidation which accounts for about 30 percent of the original mass. Also, the search teams may have missed some small fragments on the ground. The remainder of the unrecovered material is carbon fiber that was oxidized in the fire. Substantial fiber oxidation in fires had been predicted on the basis of laboratory thermogravimetric analysis coupled with fire plume dynamics and chemistry studies (ref. 9).

These observations confirmed earlier laboratory tests in which composites were burned until they were severely damaged and were subjected to mechanical agitation, airstreams, and explosives. Typical results from a large number of tests are plotted in figure 14. Single fibers accounted for less than 0.1 percent of the original fiber mass available when the composite was burned without disturbance. When tests included agitation of the debris by falling masses or gentle breezes, single fibers accounted for 0.001 to 1 percent of the original fiber mass available. Only when nearly sonic air blasts or explosives agitated the debris did single fibers account for more than 1 percent of the original fiber mass.

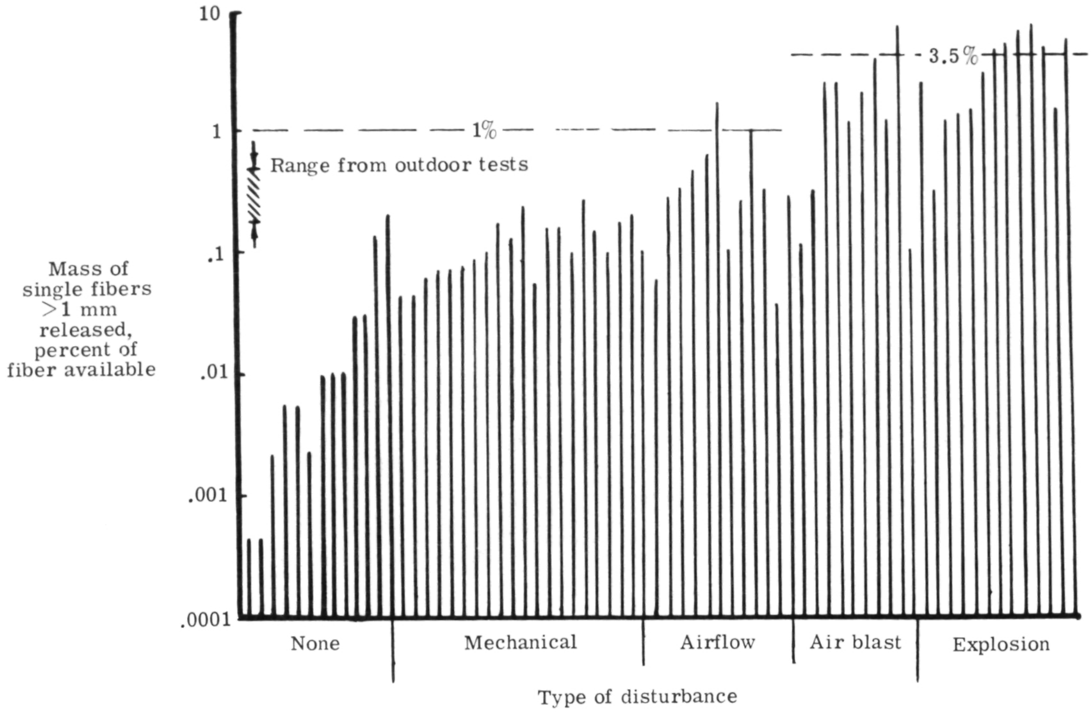


Figure 14.- Results of laboratory fiber-release tests.

The horizontal dotted lines in figure 14 show the values of 1 and 3.5 percent, which were chosen to represent the upper bounds of these data in the risk assessment. For those aircraft crash fires that involved no explosion, 1 percent of the originally available fiber in the burned composite was assumed to be released as single fibers longer than 1 millimeter. In the remaining crash fires, explosions were involved and 3.5 percent of the available fiber was assumed to be released.

Fiber-release rate.- The rate of single-fiber release was determined in three outdoor tests by active sensors hung on the Jacob's ladder. Recordings from these instruments indicated essentially a constant rate of release of single fibers through the duration of the fire. A typical cumulative history of fibers passing one sensor is shown in figure 15. The initial delay in sensing fibers was the time required for fibers to be released from the matrix and be transported to the sensor. As the fire went out after 20 minutes, the rate of fibers passing the sensor dropped to zero.

Length of fibers.- Single fibers observed in these studies were much shorter than originally expected. To assess electrical risk, only those fibers longer than 1 millimeter

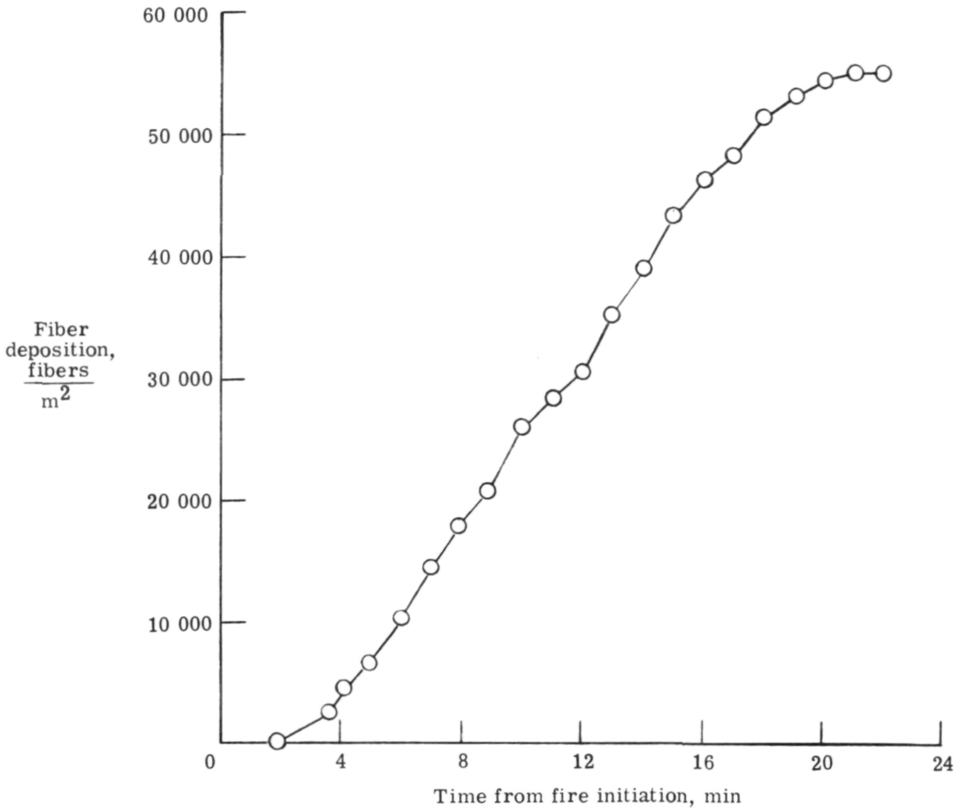
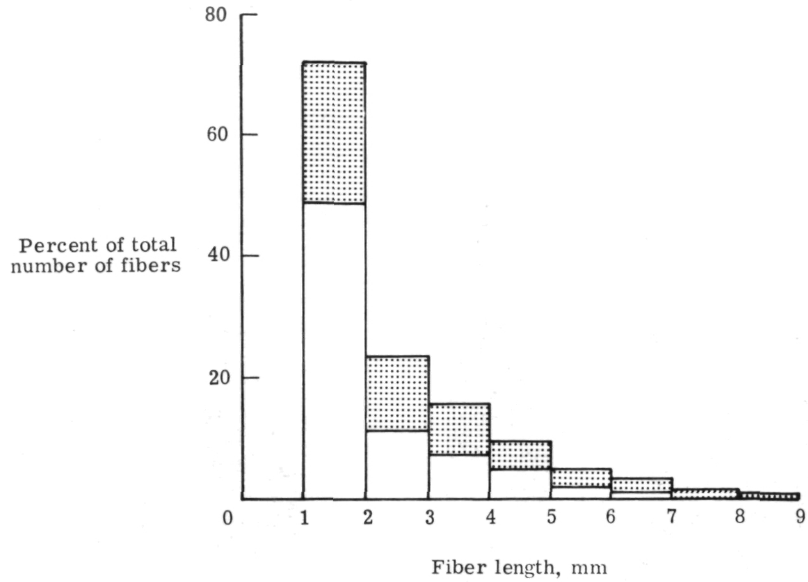


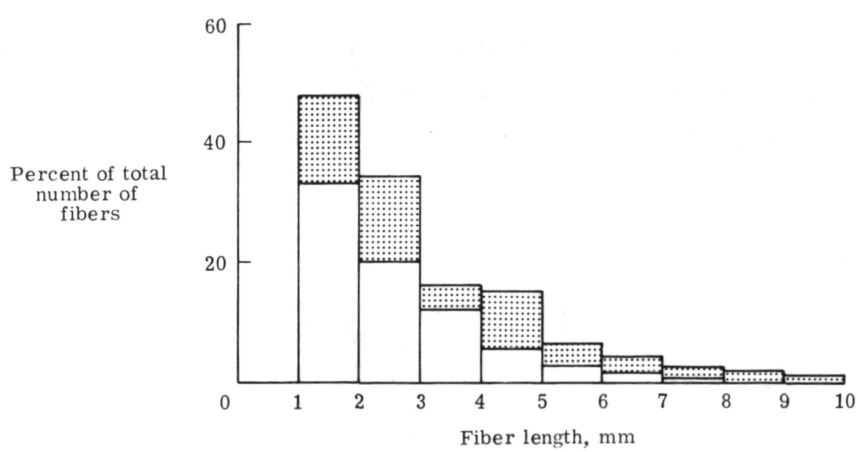
Figure 15.- Cumulative history of fibers released during burning of composite components in a 20-minute aviation-jet-fuel fire.

were of interest. Their lengths were distributed as indicated in figure 16(a) for laboratory tests. The shaded portions of the figure represent the range of data taken in a large number of fire-release tests with and without significant agitation of the debris. A similar distribution of lengths (fig. 16(b)) was observed in seven outdoor tests. Considering the many variables in the tests, the agreement is excellent. Fiber-length distribution appears to be independent of test conditions. In each set of data, the preponderance of fibers were between 1 and 3 millimeters long, and very few fibers were longer than 4 millimeters. The mean length was between 2 and 3 millimeters. A 2-millimeter mean length is equivalent to 5×10^9 fibers per kilogram. This number was used in the risk assessment computations.

Investigation of fibers shorter than 1 millimeter (refs. 9 and 31) established that these shorter fibers constituted 67 to 74 mass percent of the total single fibers released by fires alone, and up to 98 mass percent of those released in fires accompanied by



(a) Released in laboratory tests. Shaded regions indicate ranges from tests with and without disturbance.



(b) Released in outdoor aviation-jet-fuel fire tests. Shaded regions indicate ranges for seven tests.

Figure 16.- Distributions of lengths of fibers longer than 1 mm.

explosions. The electron micrographs of burned fibers in figure 17 illustrate why short fibers were found. The long lengthwise markings are sites where the fiber had been

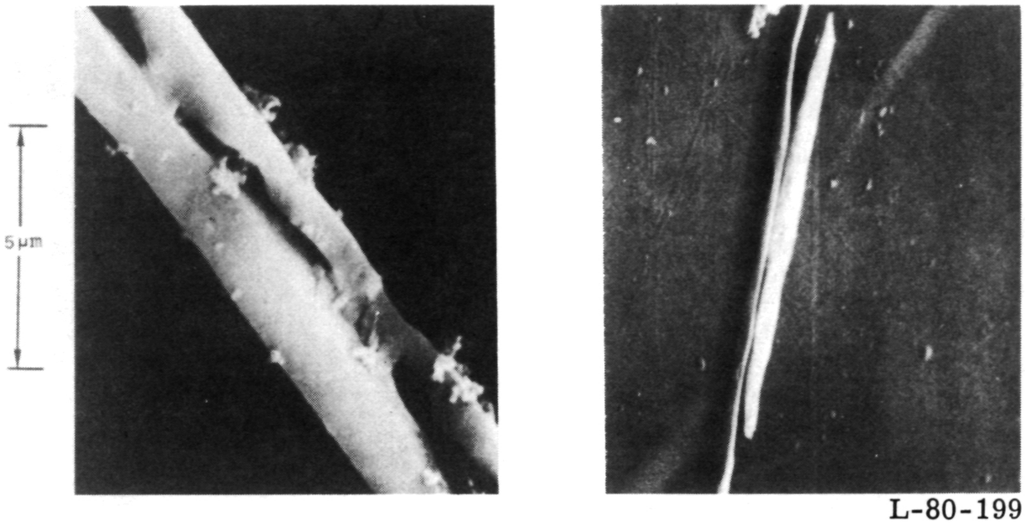


Figure 17.- Photomicrographs of fire-oxidized fiber.

preferentially oxidized. The preferential attack made the fibers vulnerable to breakage by minor disturbances. This oxidation was aggravated because of relatively high concentrations of metallic ion impurities (e.g., sodium) sometimes present in the acrylic precursor to the carbon fibers (ref. 32).

Fiber diameters.- The phenomenon that led to short fibers almost always led to small fiber diameters. The diameters of sample fibers longer than 1 millimeter released in the seven outdoor tests were determined. The results are shown in figure 18. Clearly,

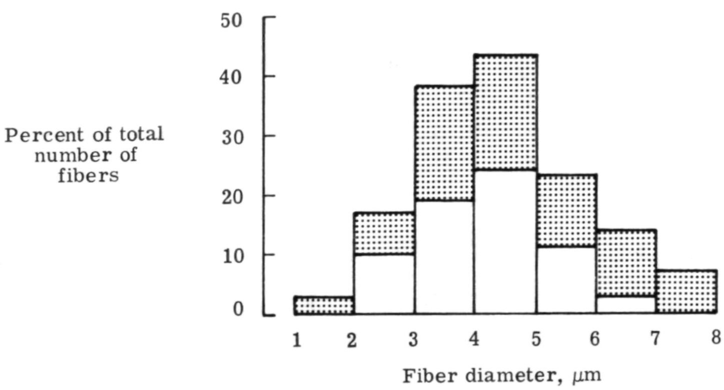


Figure 18.- Distribution of fiber diameters for fibers longer than 1 mm released in outdoor aviation-jet-fuel fire tests. Shaded regions indicate range of results for seven tests.

most diameters were reduced significantly from the original 7 micrometers. The mean diameters of these samples were 4.0 to 4.7 micrometers. The shaded portions of the figure represent the ranges of values observed.

The possible health considerations of fibers which were smaller than those of electrical concern led to a preliminary investigation which showed that 95 percent of the fire-released carbon fibers were less than 1 millimeter long. A more extensive study (ref. 32) was then conducted to assess the prevalence of fibers which were conservatively defined to be of potentially respirable size (less than 80 micrometers long, less than 3 micrometers in diameter, and with length-to-diameter ratios from 3:1 to 10:1). The results of that study disclosed that no more than 23 percent of the fibers released from jet-fuel fire tests fell in that size domain. As seen in figure 17, the overall fiber diameter had been reduced drastically from the original 7 micrometers to approximately 3 micrometers; and the splitting, or fibrillation, that seems imminent could reduce it further to approximately 1 micrometer. As indicated earlier, large portions of carbon fiber had been completely consumed by oxidation.

In the absence of any evidence that carbon fibers of any size could have adverse health effects on humans (except for typical cutaneous allergic reactions to many fibrous substances), comparisons were made with the quantities of concern in the case of other fibers. With the conditions and some of the results of one of the large-scale, outdoor jet-fuel fire tests as the scenario for an extreme-case aircraft crash fire, a maximum concentration of respirable-sized carbon fibers which was carried downwind in the densest part of the smoke plume was computed (ref. 32). A concentration of 5×10^6 fibers per cubic meter was found for a point close to the fire. The total exposure to carbon fibers from that extreme-case accidental crash fire was predicted to be less than 0.5 percent of the maximum occupational exposure recommended by the National Institute for Occupational Safety and Health (NIOSH) for exposure in a 10-hour workshift to respirable-sized fibrous glass or other man-made fibers.

Field tests conducted during the outdoor tests showed lower values than had been calculated for the extreme case in reference 32. The actual total exposure of potentially respirable fibers 140 meters from the fire for the entire test was less than 0.16 percent of the NIOSH limit recommended for 10-hour exposure to fibrous glass fibers.

This combination of computed and experimental data for potentially respirable fire-released carbon fibers indicated that low quantities are released from burning aircraft composite structural parts, and these fibers are not known to have adverse physiological effects on humans.

Electrical resistance.- Measurement of electrical resistance of fire-released fibers of different diameters indicates that fiber resistance varies approximately as the inverse of the cross-sectional area of the fiber (refs. 11 and 25).[4]

FIBER TRANSPORT

Four separate topics relating to fiber transport were investigated:

- Plume rise: how do the fibers released during the fire rise with the buoyant gases?
- Dissemination: how does the cloud of fibers disperse in the atmosphere and finally settle?
- Resuspension: how are once-deposited fibers picked up by air currents at a later time?
- Transfer: how do fibers enter buildings and enclosures to reach electrical equipment?

These four topics are common to many pollution problems and, in most instances, this study adapted existing models to the present problem and determined specific fiber-related parameters for the existing models.

Plume Rise

The study assumed that single fibers would be freed from the burning composite parts and rise with the combustion products. The model developed by Briggs (ref. 33) for the rise of hot gases from smokestacks was used to calculate the height to which the fiber cloud would be lofted. This model uses the fuel burning rate and the atmospheric conditions to calculate a height at which the heat from the gases has been sufficiently diluted to make the cloud neutrally buoyant. For accident simulations involving explosion, the fibers were assumed to be released outside of the buoyant fiber plume and not lofted. That condition led to the most severe ground-level exposures.

Dissemination

Many mathematical models exist for the transport of particles in neutrally buoyant clouds. These models have been verified by comparison with a large data base from

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[4]The data on the resistance of burned fibers in reference 3 are incorrect because of a measurement technique error. The data and analyses of references 11 and 25 show that fire-released fibers have a higher resistance than was reported in reference 3.

pollution studies with gases such as industrial sulfur dioxide, with liquid droplets such as agricultural sprays, and with solid particles such as fly ash from smokestacks. Those models are based on the dispersion of the particles by natural turbulent mixing of the atmosphere. The only property of the pollutant particle considered in these models is the still-air fall velocity. The fall velocities for single carbon fibers 7 micrometers in diameter were measured and calculated (ref. 34) to be 20 to 30 millimeters per second. These values are in the range for which the existing dissemination models were developed and effective.

In most pollution problems, a threshold of exposure exists below which the effects of the pollutant can be ignored. Therefore, the existing models have been developed with emphasis on the accuracy of the peak values of contamination, and with less emphasis on the accuracy of the very low contamination very far downwind. Because the carbon fiber contamination problem may have no lower threshold of sensitivity, the dissemination models had to be evaluated to very low concentrations and, hence, to distances much beyond those to which they had been tested previously. Because an experimental evaluation appeared prohibitively difficult, an analytical approach (ref. 35) was used to ensure that the models were conservative over these large distances.

For the further detailed discussions of dissemination, the following terms and definitions are used:

- Concentration: The basic measure of particle pollution in terms of number of particles per unit volume; its symbol is C.
- Exposure: The integral of the concentration of particles over the time during which that concentration has an effect; its symbol is E and its units are fiber-sec/m^3.

$$E = \int C \, dt$$

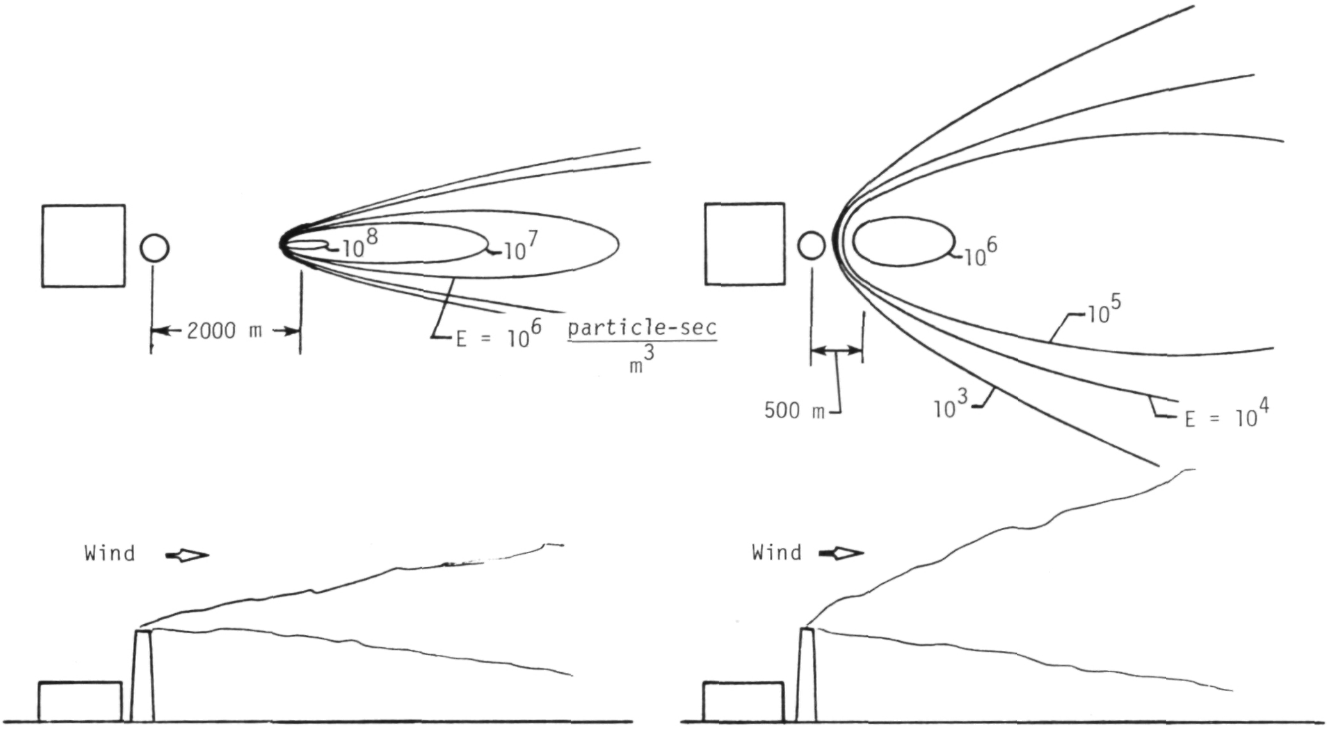
- Deposition density: The number of particles per unit area of horizontal flat surface; its symbol is D. The deposition at a point is the product of the total exposure at that point and the fiber fall velocity v_s; that is,

$$D = Ev_s$$

The dissemination models used in the risk assessment predict the expected exposure levels resulting from a known number of fibers released into the air. They are sensitive to meteorological conditions which determine the extent of turbulence in the atmosphere such as temperature gradients, insolation, and wind velocity. For these

models, all weather conditions have been divided into six categories ranging from stable, through neutral, to unstable (ref. 36).

Figure 19(a) illustrates a factory smoke plume in a nighttime stable atmosphere and the predicted exposure pattern for a release of 1 billion particles. Figure 19(b) shows a



(a) Stable atmosphere.

(b) Unstable atmosphere.

Figure 19.- Atmospheric dissemination and exposure (E) footprint for particles in a factory smoke plume.

similar event for a sunny day with light winds, a condition labeled unstable because air heated near the ground rises by convection through the higher air layers until it reaches an inversion layer. In unstable weather, the plume rises higher and disperses faster. The ground-level exposure pattern covers a larger area but the exposure values are lower than for the stable atmosphere. For each weather category, the models use an average spread angle for the cloud based on smoke-plume observations and a limiting height to which the cloud can rise.

Gaussian dissemination models (refs. 37 and 38) treat a pollution source as a point source growing in two dimensions such that the concentration profile is always a Gaussian distribution. That distribution represents a good estimate for plumes of long duration such as those from industrial smokestacks. However, there is much short-term variability in a fire plume. Thus, the Gaussian description should not be interpreted as a

real physical description, but rather as the average description for many similar short-term events under the same meteorological conditions. To account for the growth limitations set in the vertical direction by the inversion height and by the ground, a light-beam analogy is used to reflect the growing "beam" (the particle cloud) back inside the turbulent convection layer. The appropriateness of the Gaussian models and the light-beam analogy were analyzed (ref. 35). For short carbon fibers and their range of fall velocities, these models produced results which agreed very well with results from a much more complex full-diffusion analysis. Therefore, the risk calculations were made with these models.

For mathematical convenience, most dissemination models assume that all particles are released from a single point source. The height of the point source above the ground is an important variable in determining the location and strength of the maximum ground-level exposures. Figure 20 shows the exposure along the downwind centerline for two

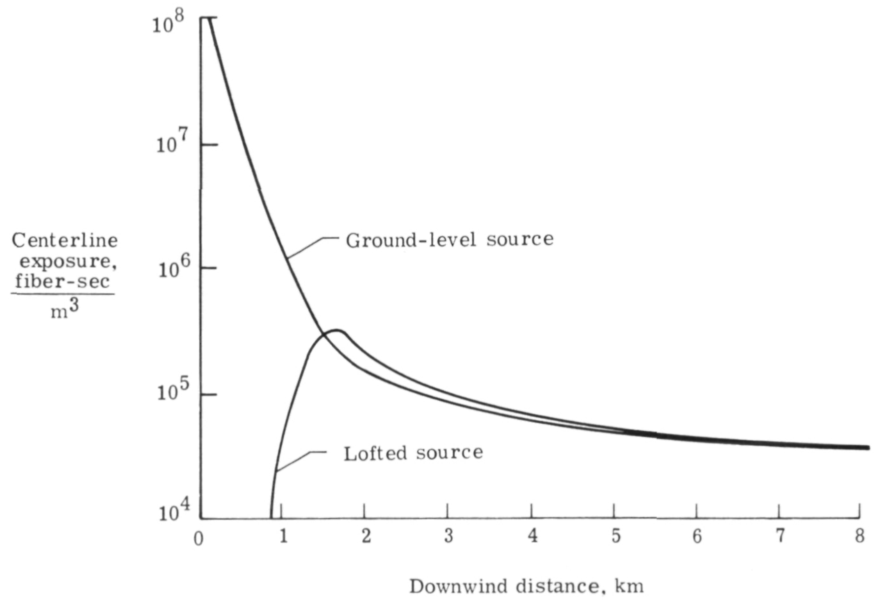


Figure 20.- Exposures from lofted and ground-level sources.

releases of 1 billion fibers each. In one example, the fibers are released by an explosion at ground level. The point-source calculation predicts singular behavior for the exposure at the release point but only a small wedge of ground area is exposed to these levels. In the other example, the fibers are lofted to 200 meters in a neutral atmosphere. The results differ greatly for the first 2 kilometers, but are essentially identical farther downwind. The integrated effect is small.

In the large-scale outdoor jet-fuel fire tests (refs. 10 and 28), the exposure measured showed that not all the fibers were lofted with the hot plume. The best agreement between test and theory was obtained with the assumption that only half the material was lofted with the fire plume and the other half was released at ground level. Similar results have been reported (ref. 39) for the fraction of smoke lofted with the fire plume. That study showed that an average of 40 percent of the smoke drifted downwind without any lofting. The risk analysis described in a later section did not account for this effect. However, in a sensitivity study, the risk from explosions releasing 3.5 percent of available fiber at ground level was three times the risk from fires releasing 1 percent of available fiber at the plume rise height. This ratio is roughly the ratio of fiber released and suggests that the height of the fiber source is not an important consideration in predicting total risk.

The relatively unimportant influence of plume height on total risk is further illustrated by recognition of one important invariant that relates all exposure distributions. Because the deposition in a small area dA is

$$D\,dA = v_s E\,dA$$

the total deposition over the whole area A on which particles can be distributed is

$$\int D\,dA = v_s \int E\,dA$$

This must be equal to all the fibers initially released, so that if N is that number of fibers,

$$N = v_s \int E\,dA$$

This area integral of exposure is a constant, dependent only on the number of fibers. If the fibers are uniformly dispersed over an area A, the product of the area covered and the exposure over the area is a constant

$$EA = N/v_s$$

Figure 21 is a plot of this interrelation between exposure and area for release of any given mass of fibers of 2-millimeter mean length. The dashed line shows that for the worst-case aviation accident postulated, the area of one typical suburb could be covered to an exposure of 5×10^6 fiber-sec/m^3, or that the area of a typical city could be covered to an exposure of 5×10^5 fiber-sec/m^3. These exposures are values outside buildings.

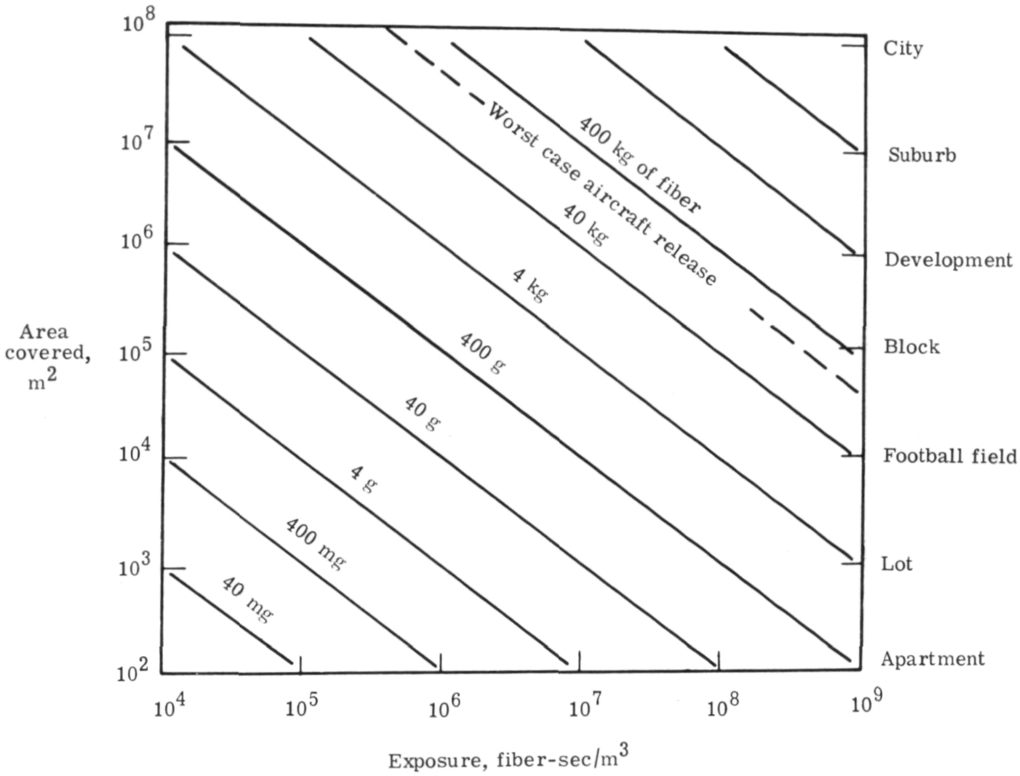


Figure 21.- Parametric plot of carbon fiber exposure/distribution. Mean fiber length of 2 mm.

Resuspension

Resuspension of deposited particles is a phenomenon which occurs in dust and sand storms and has been studied to understand many pollution problems. But models applicable to sand and dust were considered unsuitable for carbon fibers because the aerodynamic characteristics of cylindrical fibers are quite different from those of more nearly spherical dust and sand. Therefore, a study was conducted to monitor the resuspension of carbon fibers from a desert area where about 50 kilograms of cut fibers had been deposited (ref. 40). The fiber flux from that area was monitored and analyzed at regular intervals for more than 3 years. As shown in figure 22, the initial rate of resuspension was highest, and very few fibers were being released from the area after 3 years. The total number calculated as having been resuspended was less than 1 percent of the number originally deposited. An analysis of the length of the airborne fibers shows that, after 3 years, only 1-millimeter fragments were being resuspended. The average length of the resuspended fiber is shown in figure 23.

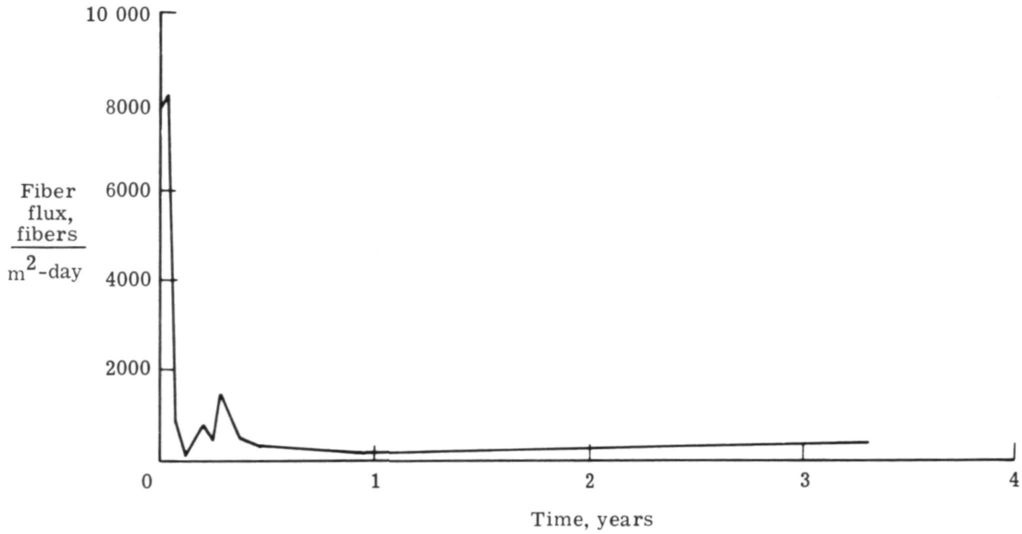


Figure 22.- Carbon fiber resuspension with time.

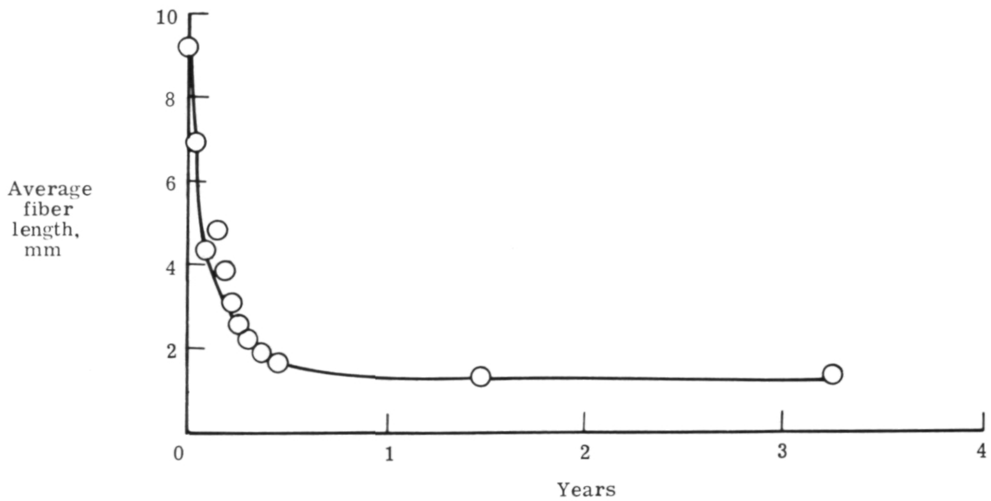


Figure 23.- Change in length of resuspended fibers with time.

An analysis of the desert surface showed that many fibers and fiber clumps had been washed into depressions and were covered with soil, while others had been trapped under the roots of desert vegetation. Other surfaces would presumably have different resuspension characteristics. Water, forest, and other high vegetation probably would suppress resuspension completely, while paved surfaces probably have high resuspension rates. However, washdown from rain would limit the time over which the material was available for resuspension from paved surfaces (ref. 41).

On the basis of these findings, the contribution to the exposure from resuspended particles was expected to be small compared with the original exposure. Therefore, the risk assessment was made without any contribution from resuspended particles.

Transfer

In this study, the fiber transfer function was defined as the ratio of exposure inside a building or enclosure to the exposure outside. The electrical and electronic equipment which is vulnerable to carbon fibers is seldom exposed outside of buildings. Instead, buildings, filters, and cabinets protect such equipment. The applicable transfer functions were studied to determine the degree of protection offered by such enclosures (ref. 25).

Airflow models were developed to determine the possible flow of fibers into buildings and to establish the transfer functions. These models indicated that airflow rates, filter factors, fiber fall velocity, building height, and floor area all influenced the transfer functions. Although airflow data for ventilation and leakage were available from building standards, filtration data through filters and screens had to be determined.

In experimental studies (refs. 25 and 42 to 44), the filter effectiveness for numerous filter types was established. Figure 24 shows an experimental correlation between the

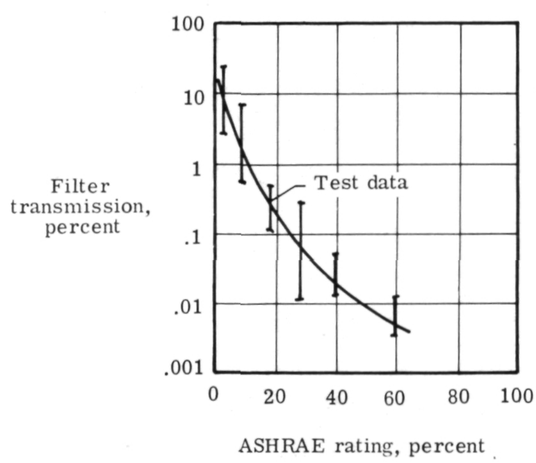


Figure 24.- Filter transmission for virgin fibers 3 mm long.

filter transmission factor and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Dust Spot Rating, a standard industrial rating system for filters. These data indicate that many industrial filters pass fewer than 10 percent of the fibers they encounter and some pass far fewer. Ordinary window screens were found to transfer only 10 percent of the 3-millimeter fibers striking them. Naturally,

the effectiveness was higher for fibers than for spherical particles of the same diameter, the normal rating basis for filters. Also, the filters were more effective at stopping long fibers than short fibers. As a result, the fiber-length distribution after filtration was relatively shorter than before filtration. The risk calculations ignored this effect and conservatively used the fiber-length distribution measured at the fiber source.

Analytical studies and experimental results showed that fibers break up in significant numbers when they impact surfaces at speeds near 50 meters per second in high-velocity air-handling equipment. Simulation tests (ref. 25) showed that only fiber dust could be expected to enter an aircraft air-conditioning system through the jet engine and intakes. Therefore, the in-flight transfer function for aircraft was assumed to be zero in the risk assessment.

VULNERABILITY OF EQUIPMENT AND SHOCK HAZARD

The vulnerability of electrical and electronic equipment to malfunction or damage when exposed to carbon fibers and the potential shock hazard were assessed in a systematic series of experiments. These experiments included

- Probing the circuitry with shunts of known resistance
- Exposing equipment to chopped virgin fibers in a closed chamber
- Exposing equipment to fire-released fibers

Over 150 pieces of equipment were tested, including household appliances, moderately complex electronics, and avionics. In addition, the attenuation effects of fibers on signals for airport landing aids were assessed analytically.

Because shock hazards were considered a potential threat to human life, many consumer devices were investigated for potential shock hazard (ref. 45). Of these, the toaster presented the most significant hazard. A plot of the results of tests with six toasters is shown in figure 25. These results were shown to produce less than 0.38 potential shocks per year (refs. 46 and 47). None of the potential shocks drew currents that would be considered lethal because the fiber would burn out before a dangerous level was reached. Therefore, the shock hazard was not considered further.

Test Methods

Tests with simulated fibers.- A wide range of household and other appliances were probed with a fiber simulator (ref. 45). The simulator was a hand-held probe (ref. 48) having a variable resistor to represent a carbon fiber. The control circuit for the probe measured the current flowing through the simulated fiber and simulated burning the fiber to evaluate whether a fiber-caused malfunction would persist. Consumer appliances

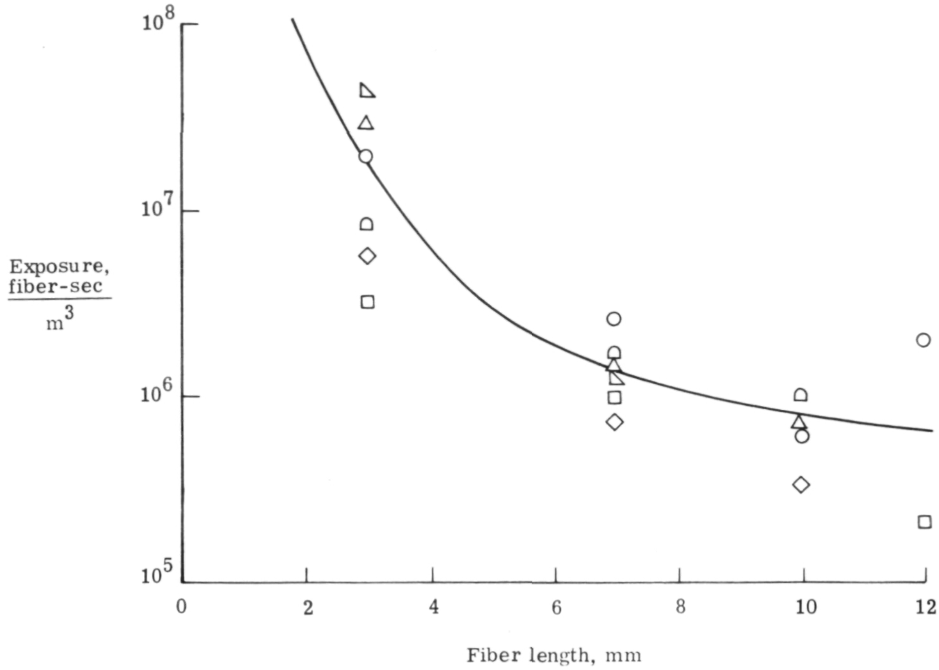


Figure 25.- Mean exposure required for short circuit to case of six toasters. Each test-point symbol represents a different manufacturer.

having electromechanical and simple electronic logic components with up to a few hundred potentially vulnerable pairs of contact points were quickly probed (ref. 45). The consumer equipment tested represented over 85 percent (total value basis) of the consumer goods in current use.

Tests with chopped fibers.- A somewhat more realistic, but more expensive, series of tests was conducted on similar appliances, but in a closed chamber into which chopped virgin fibers were blown. For most of these tests, Thornel 300 fibers were utilized because this fiber is representative of those used in aircraft structural composites. Fiber concentrations were approximately 10^3 fibers/m^3, a value that is higher than that experienced in the fire-release tests (ref. 10).

Equipment was exposed until failure or until an exposure of 10^8 fiber-sec/m^3 was achieved. This exposure deposited essentially a continuous mat of fibers on the floor of the test chamber. Although large exposures were needed to evaluate the mean exposure to failure $\bar{E}$, exposures larger than 10^3 fiber-sec/m^3 would seldom be experienced as a result of an aircraft accident.

The fibers were chopped to uniform lengths for each test, but the length was varied from 1 to 20 millimeters, the range of fiber lengths expected to be significant contributors to electrical risk.

The electrical devices under test were usually powered during the exposure, but some devices were exposed with no power to study potential failures caused by previously deposited fibers. If the devices under test were equipped with forced ventilation or were convectively cooled, these features were allowed to function as they would in a service environment. For some tests of avionic equipment, a noise and vibration environment was imposed to further simulate service conditions.

One of the test chambers used (refs. 47 to 51) is sketched in figure 26. Generally, the tests were performed with fibers falling freely in still air.

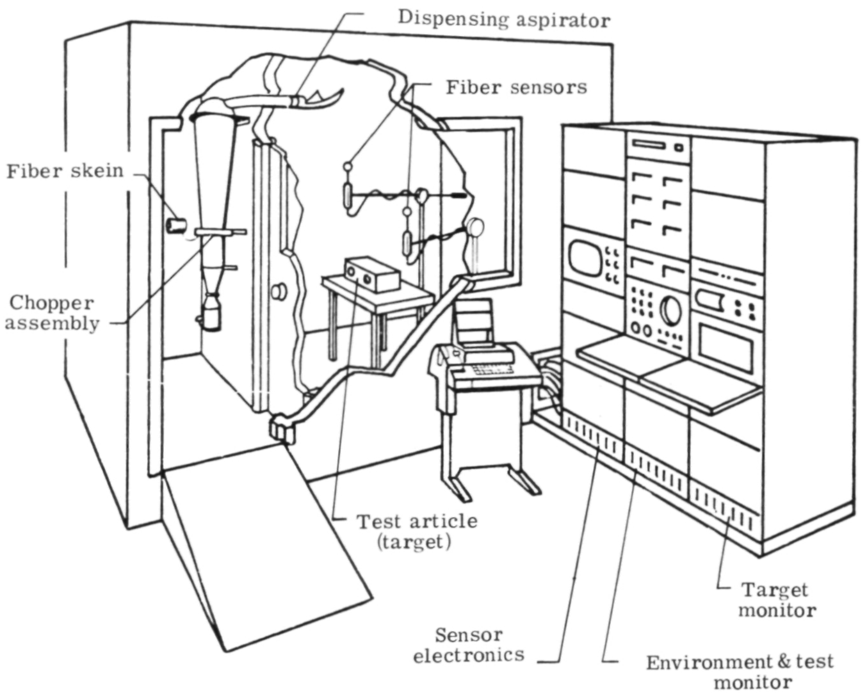


Figure 26.- NASA carbon fiber test chamber.

<u>Tests with fire-released fibers</u>.- Additional tests (ref. 11) were performed with six stereo amplifiers exposed to carbon fibers released by burning composite components in a pool fire of JP-1 fuel. The fire plume was enclosed in a horizontal tube about 6 meters in diameter which conducted it to a test section in which the electronics and test instrumentation were installed. Some of the tests were made without fibers to study whether failures were induced by the soot or heat.

Results of Fiber Exposure Tests

In general, the equipment was less vulnerable than had been expected (refs. 3, 11, 25, 45, 47, and 49 to 52). In almost all cases, the equipment was restored by vacuuming the affected circuitry.

The results of tests performed on stereo amplifiers are shown in figure 27. The vulnerability predicted from chamber tests using virgin fibers (ref. 50) was almost

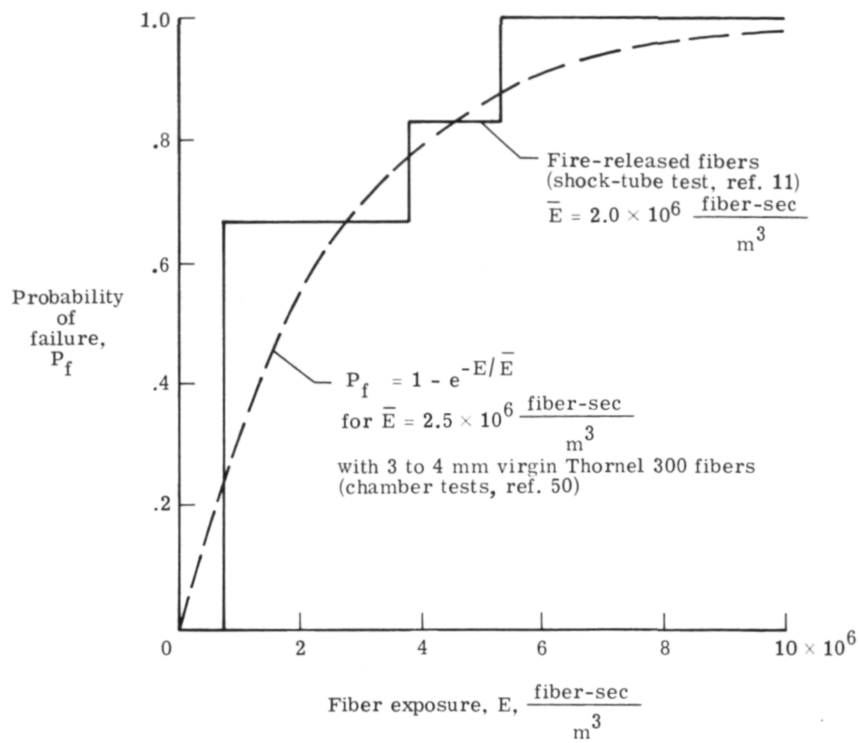


Figure 27.- Failure of stereo amplifiers caused by exposure to carbon fibers.

exactly reproduced in the fire-released fiber tests (ref. 11). Therefore the chamber tests were considered suitable for assessing vulnerability of specific equipment. The effect of increased fiber resistance (associated with the decrease in cross section of oxidized, fire-released fibers (refs. 11 and 25)) was not evident from the fire-released fiber test results. This effect should raise the mean exposure to failure $\bar{E}$ for equipment exposed to fire-released fibers over that predicted from chamber tests, and thus conservatism to the vulnerability predictions (ref. 25).

The following generalized comments characterize the vulnerabilities observed for each of several categories of equipment.

Low-voltage equipment (0 to 15 volts) was susceptible to failures if fibers could reach critical circuitry. However, many devices had few vulnerable contacts and others were well protected against penetration by fibers. Permanent malfunctions sometimes occurred because insufficient voltage was available to burn away ingested fibers. In some low-power circuits, in computers, for example, these malfunctions were errors in logic or displays. Most of the equipment found susceptible had low voltage and low

power. Low-voltage, high-power equipment, such as a battery charger and a solenoid, had sufficiently low impedance that the presence of the fibers did not cause malfunctions.

Medium-voltage equipment (15 to 220 volts) usually survived exposures to fibers because the voltage was high enough to burn out the fiber in a short time without damage to the equipment. Such short-duration phenomena may cause malfunctions, but such malfunctions are statistically unlikely because of fiber burnout. Sustained arcs were observed at voltages as low as 50 volts dc provided that sufficient power was available. However, arcs were not sustained in 60-hertz, 110- to 220-volt, single-phase equipment. Although circuit breakers and fuses interrupted the current in this voltage range during testing, no equipment was damaged. This inherent invulnerability of 110-volt devices was demonstrated by tests on appliances, motors, and thermostats.

High-voltage equipment (440 volts, 60 hertz) is used in many industrial applications. Tests of various terminal configurations indicated no sustained arcs for this voltage level on single-phase power drawn from a commercial line. Three-phase systems sometimes sustained fiber-initiated arcs that damaged connectors. This damage was limited by the circuit-protection devices employed (ref. 25). Both single-phase and three-phase circuits with normal terminal spacings sustained arcs if power was drawn from motor-generator sets because of the inductive characteristics of the supply.

Vulnerability of high-voltage distribution-system components (>440 volts) was also investigated (ref. 3). High-voltage power-system insulators (>440 volts) were found to survive exposures in excess of 10^7 fiber-sec/m^3 (for fibers 2 or 4.3 millimeters long) without flashover (ref. 3). Figure 28 is an example of these results. Because the distances across high-voltage insulators are large, multiple fibers must link together to induce flashover. Such linking is unlikely except for extreme depositions. Flashovers occurred at lower exposures ($E = 10^5$ fiber-sec/m^3) of longer fibers (9 millimeters), but such long fibers are unlikely to be released in sufficient numbers to constitute a significant hazard.

Because of the specific responsibility of the NASA study to assess the potential need for protection of aircraft, special attention was given to determining the vulnerability of avionics equipment used in scheduled commercial or general aviation aircraft (ref. 52). No equipment had mean exposures to failure $\overline{E}$ less than 10^7 fiber-sec/m^3 even when the test included noise and vibration to simulate the environment of the avionics bays in aircraft. These data, combined with airflow and filtration data pertinent to specific aircraft, were used to evaluate the risk to commercial aircraft safety and the need for protection (refs. 53 to 55). The overall safety and cost risk was insignificant and no aircraft protection was deemed necessary.

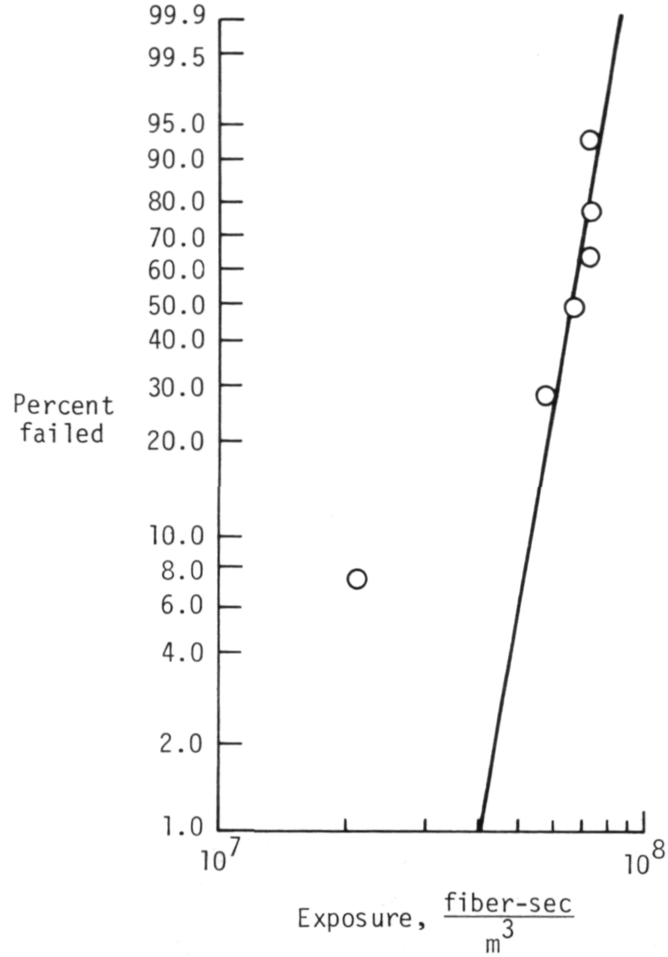


Figure 28.- Exposure to cause flashover for wet 7.5-kV pin insulator. 2 mm fibers.

Results of Fiber Simulator Tests

Detailed studies were made of the specific circuitry and failure modes in a television set, an amplifier, a microprocessor, and a number of smoke detectors (ref. 25). As expected, equipment vulnerability varied with airflow, the number of conductors exposed, and the resistance of the simulated fibers bridging those conductors. The influence of fiber resistance was demonstrated in tests of an amplifier. Fiber simulator probe tests indicated that Thornel 300 (T-300) fibers (resistance 600 kΩ/m) would produce approximately seven times as many malfunctions as would higher resistance (8 MΩ/m) Celion DG-114 fibers (fig. 29). Exposure tests with real fibers (ref. 50) confirmed the relationship, and showed that the mean exposure to failure $\overline{E}$ for DG-114

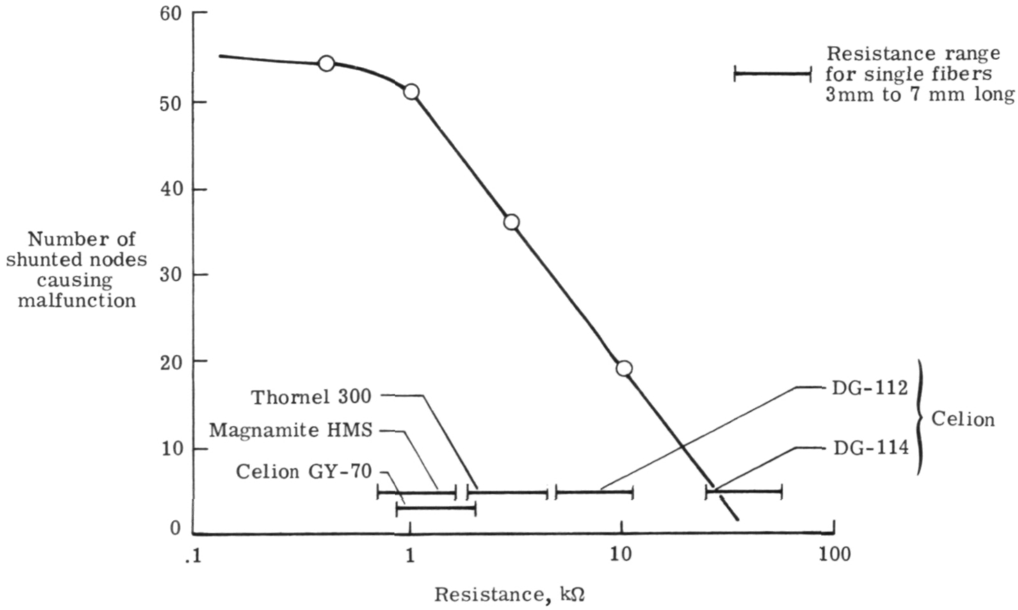


Figure 29.- Amplifier sensitivity to shunt resistance.

fibers was an order of magnitude greater than for T-300 fibers. Figure 30 shows the results of tests in which adjacent and alternate pins of components in a microprocessor were shunted using a fiber simulator. Spacings between adjacent pins were 1 to 2 millimeters and between alternate pins were 3 to 5 millimeters. Resistances larger than 1000 ohms did not produce a significant number of failures. From these results, a negligible number of elements in this device would be susceptible to failure from T-300 fibers 2 millimeters long or longer. Under direct exposure in a test chamber, T-300 fibers did not produce a fault even at exposures larger than 10^8 fiber-sec/m^3.

Vulnerability Considerations

Electronic and electrical equipment contains large numbers and various types of discrete and integrated components, circuit board configurations, contact spacings, ventilation schemes, and filtering devices (if present) and operates on voltage sources ranging from a few volts to many thousands of volts. Therefore, only a few general observations regarding vulnerability were possible. Estimates of the vulnerability of equipment was based on these observations.

Ventilation.- The number of fibers which may fall on open electrical equipment is proportional to the concentration, time of exposure, and free-fall rate of the fibers. For this reason, vulnerability is best correlated with exposure E (the integral of concentration over time) for a given system. Case-enclosed electronics generating low convection velocities are relatively invulnerable. When the dissipated power is sufficient to

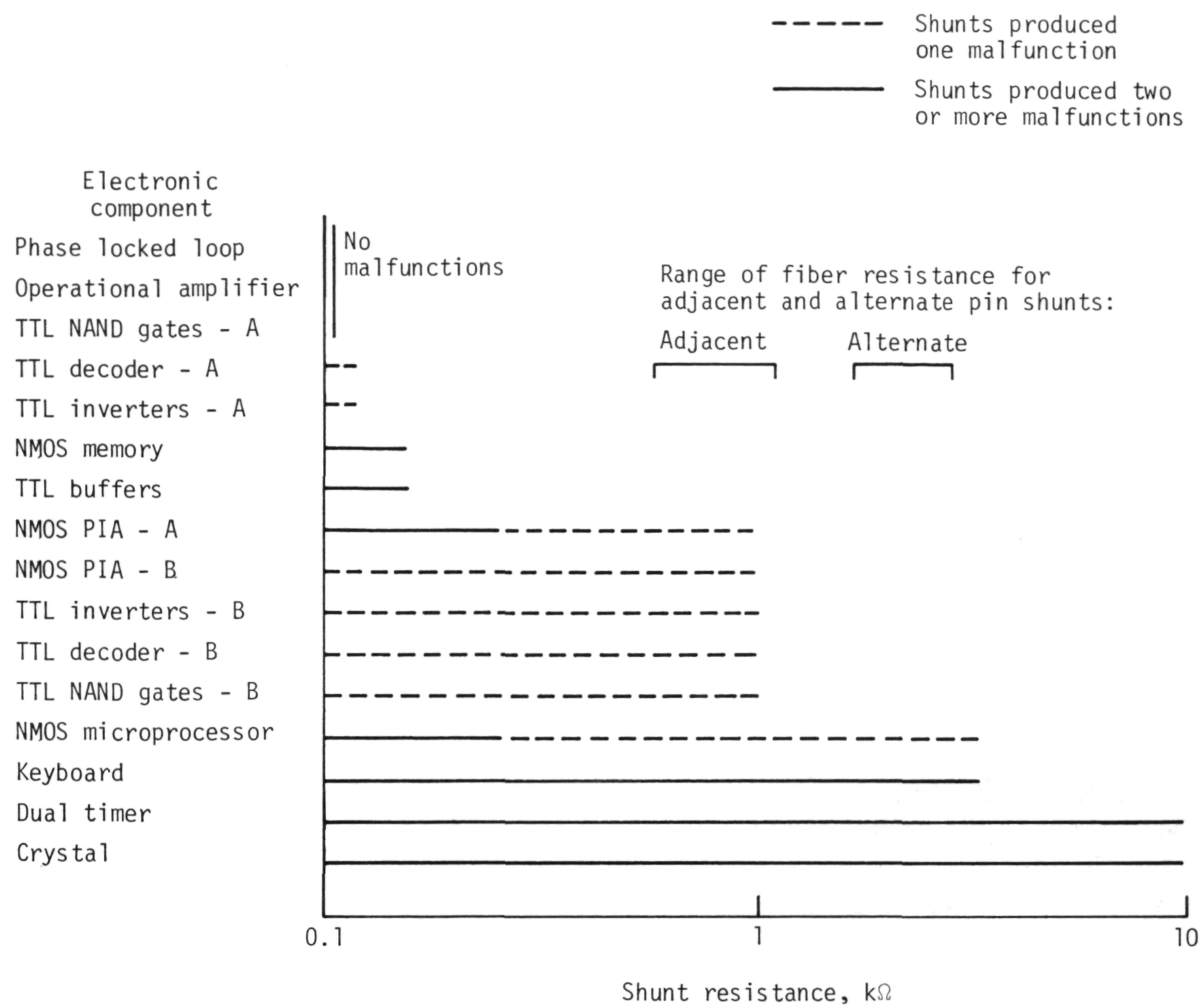


Figure 30.- Microcomputer component sensitivity to resistance of shunt simulating Thornel 300 fibers.

generate convective air velocities larger than the fiber fall velocity, the induced circulation may entrain fibers and, thus, increase deposition density and system susceptibility. The most susceptible systems are those cooled by unfiltered forced air (refs. 25, 50, 52, and 56).

Electronic and electrical circuit and part characteristics.- As shown in figure 31, high vulnerability was exhibited by older equipment using vacuum tubes and other high-impedance components. Modern electronic equipment has highly integrated circuits with few discrete parts and, in general, operates with no ventilation and low power. Thus, it is correspondingly less vulnerable.

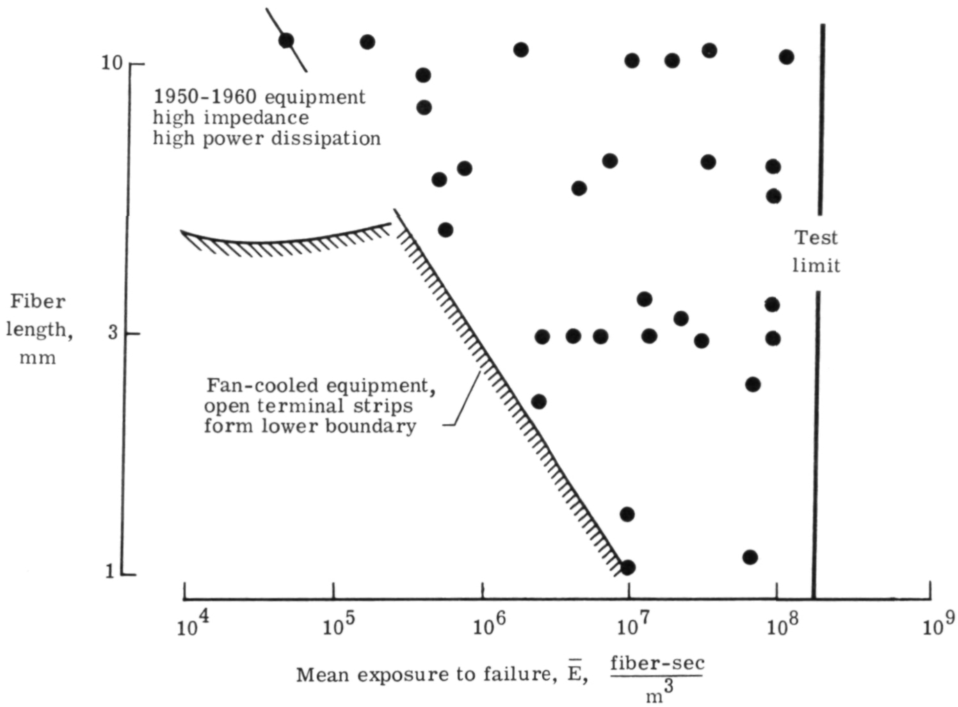


Figure 31.- Mean exposure to failure for vulnerable equipment.

Fiber length effects.- All of the chamber testing was accomplished with single-length fibers. However, the fibers were released in fires at many lengths. In most cases, the following exponential fiber-length distribution function gave a good approximation of the fire-released distribution of lengths:

$$F(\ell) = \left(\frac{1}{\ell_a}\right) \exp(-\ell/\ell_a)$$

where ℓ_a is the average fiber length chosen empirically to fit the equation to the data. From reference 57 the integrated effect of simultaneous exposure of electronics to fibers at a variety of lengths can be estimated by assuming that all fibers released are of length ℓ_a and determining $\overline{E}$, from its experimentally determined variation with fiber length, at a length equal to $\ell_a \sqrt{2}$. This relationship is exact where $\overline{E}$ varies inversely with fiber length squared, and is a good approximation for the full range of experimental variations encountered.

In most of the experiments performed, fibers were collected and counted, and the length averaged for only those lengths exceeding 1 millimeter. For these experimental results, as shown in reference 57, the observed average length should be reduced by 1 millimeter to account for the shorter fibers that were not counted. When this was

done, the preponderance of data indicated an average length of about 2 millimeters, and the $\overline{E}$ for each device obtained with $2\sqrt{2}$ millimeter fiber length was used in the risk analysis.

Although fibers shorter than 1 millimeter were present in significant numbers, they did not contribute appreciably to the electrical hazard identified in this investigation because the equipment tested seldom had conductors spaced closer than 1 millimeter. Individual fibers shorter than 1 millimeter were physically incapable of producing malfunctions. The linking of short fibers, say 0.5 millimeter long, to bridge a 1 millimeter or longer gap is unlikely at exposures below about 10^9 fiber-sec/m^3 (ref. 58). Fibers shorter than 1 millimeter released in realistic fires are expected to provide maximum exposures that are several orders of magnitude lower (ref. 57).

The possible risk for equipment having conductors placed closer than 1 millimeter apart was examined analytically (ref. 57). The mean exposure to failure $\overline{E}$ was assumed to be inversely proportional to the fiber length squared because such a power law was found to approximate experimental data for much of the equipment tested in this study. The exponent 2 was chosen in order to be on the safe side of observations; the lowest exponent observed for any unit tested was 2.5. The fiber-length spectrum with the largest numbers of short fibers observed in this investigation was assumed for a hypothetical incident. The contribution to overall probability of failures caused by particular fiber lengths was then calculated. For the particular spectrum used, all fibers shorter than 1 millimeter contributed only 15 percent of all potential failures. Equipment, with such closely spaced conductors, is likely to operate at low power, use coated circuitry, and be housed in well-sealed enclosures. All these factors render such equipment nearly immune to carbon fiber electrical problems.

These observations justified the emphasis of this study on electrical risk from fibers longer than 1 millimeter.

Attenuation of Electromagnetic Signals

A theoretical study (ref. 25) was performed to quantify the degradation of instrument landing aids due to attenuation of radio-frequency signals by deposits or clouds of carbon fibers released from a fire involving carbon fiber composite material. The two situations considered were (1) carbon fiber deposits on antenna radomes and (2) transmission paths intersecting fire plumes with significant concentrations of carbon fibers. The current Instrument Landing Systems (ILS) operating at 75, 110, and 330 megahertz, and the future Microwave Landing Systems (MLS) operating at 1 and 5 gigahertz were considered. Maximum fiber concentrations in clouds of 10^3 fibers/m^3, maximum fiber depositions on radomes of 10^4 fibers/m^2, and maximum fiber length-to-diameter ratios

of 1000 were assumed. No bias errors were predicted and the predicted attenuations were negligible (<1 decibel) except for MLS, 5-gigahertz transmission through a fiber cloud (fire plume) which is oriented directly along the path to an approaching aircraft. In this case, the attenuation may be enough to reduce the system operating range by approximately 30 percent. This means that the guidance system would provide the correct path to the ground even when the aircraft was flying the approach through a continuous cloud of carbon fibers, but that guidance signals might not be acquired beyond 70 percent of normal range.

Application of Results

Experiments on vulnerability of electrical and electronic equipment were generally performed with five or more exposures to failure to determine the mean exposure to failure $\overline{E}$. This was accomplished at each of a number of fiber lengths. In realistic situations, the actual exposure E is likely to be one or more orders of magnitude smaller than $\overline{E}$. To apply the observations to these practical exposures, analysis (refs. 58 and 59) shows that the probability of failure P_f due to exposure to single fibers is

$$P_f = 1 - e^{-E/\overline{E}}$$

When $E/\overline{E} \leqq 0.1$, this probability is closely approximated by $P_f = E/\overline{E}$. All risk assessments made in this study employed the exponential failure law or this linear approximation. The resulting failure probabilities at low exposures are inherently on the safe side (perhaps by orders of magnitude), because the only other modes of failure require multiple fibers to link together and the probabilities of such occurrences are very much smaller.

FACILITY SURVEYS

Objectives of Surveys

Facilities were surveyed to provide the data required to make economic predictions of carbon-fiber-induced incidents throughout the nation. The 63 facilities listed in table III were visited by technical teams. The list includes representative public, utility, commercial, and industrial facilities.

TABLE III.- SUMMARY OF FACILITIES SURVEYED

Type of facility	No.	Type of facility	No.
Public		Commercial	
Hospitals	7	Department stores	2
Air traffic controls	6	Financial institutions	2
Airports-airlines	3	Radio and television stations	6
Police headquarters	2	Analytical laboratories	1
Fire dispatch	2	Manufacturing	
Post offices	1	Meat packing	1
Traffic control	1	Textile mill	1
Utilities		Garments	1
Telephone exchanges	3	Pulp and paper	1
Power generation and distribution	3	Publishing	2
Refuse incinerators	2	Textile fibers	1
AMTRAK Railway System	1	Toiletries	1
		Steel mills	2
		Wire, cable	1
		Electrical equipment	6
		Automotive fabrication and assembly	4

The following data were gathered for each facility surveyed:

- Listings of equipment by types (computers, controls, instruments, etc.) and quantities
- Description of the way equipment was employed in the operation of the facility (part of an automated line, one of many identical units, etc.)
- Description of the ventilation systems and existing protective elements (separate rooms, shielding, sealed cases, coated circuit boards, etc.)

The listings of equipment guided the selections of items for exposure testing which, in turn, provided a basis for selection of $\overline{E}$ (mean exposure to failure) used in the prediction of failures. The mode-of-use descriptions supported the definition of the economic impact from an electrical failure in such terms as repairs, lost worker time, lost production, and spoiled product. The data from the ventilation system and protective measures supported the calculations for transfer functions into buildings and equipment. The specific descriptions of air-conditioner filters guided the selection of candidate elements for exposure testing.

The surveys found that many plants operate electrical equipment in environments such as dust, moisture, corrosive liquids, or combustible fluids. Protection of equipment from such environments also effectively shields it from airborne carbon fibers. The surveys identified that portion of industry which might be vulnerable and estimated the degree of that vulnerability. Because failures of electrical equipment in hospital operating rooms and air traffic controls could threaten human lives and failures in power generating stations and telephone exchanges could adversely affect entire communities, these activities were studied in detail.

The following paragraphs present the results from the surveys.

Public Facilities

Public facilities include those areas where electronic or electrical equipment performs life-critical functions, such as in hospital operating rooms, in air traffic control centers, or in communication systems for ambulance, police, and fire units. Hospital operating rooms, intensive-care units, and cardiac-care units are equipped with air-conditioning and filtration that removes airborne contaminants; such filters also remove carbon fibers from the air. Air traffic control towers are generally equipped with special air-conditioning systems to cool the many electronic items employed which generate considerable heat. Remotely mounted radars and transmitters are protected from weather and are shielded from radio-frequency interference. This combination of protection would also prevent carbon fibers from entering the systems (ref. 2). Airport terminal buildings have special ventilation systems with activated carbon filters to remove kerosene fumes and other contaminants found at airports; such filters also trap carbon fibers. Two-way communication with emergency vehicles, such as ambulance, police, and fire units, frequently involves more than one dispatcher working with more than one vehicle. An interruption at one dispatcher location would not disable the entire communication system. Within a vehicle, the road environments of heat, vibration, moisture, and corrosion dictate the use of either sealed or otherwise well-protected electronic units (ref. 3). The surveys of these areas could not identify any threats to human life or safety.

Other public facilities contained equipment which could be subject to failure caused by airborne carbon fibers. These installations had identifiable responses that would limit the impact of a failure incident. For example, in a post office, the failure of an electronic sorter results in heavier loads on alternate units or forces a return to hand sorting while the unit is repaired. For equipment in such public facilities, the economic impact of carbon-fiber-induced failures would usually be the cost of troubleshooting and repair.

Utilities

Electrical failures in telephone exchanges or electrical power stations could have an important impact upon a community. The surveys revealed that modern electronic exchanges are housed in sealed, air-conditioned buildings offering little or no entrance for airborne carbon fibers and, thus, are invulnerable to damage. Older exchanges are more accessible; carbon fibers could enter and cause some elements to fail. However, much of this equipment operates in the voltage range considered immune to fibers. Telephone exchanges contain large numbers of the same basic elements of equipment operating with continuous maintenance. In general, failures and malfunctions are located and corrected within 15 minutes.

In power generation and distribution, only the newer generating stations utilize electrical circuitry which operates in the voltage range considered sensitive to carbon fibers, and all the critical items are located within the control rooms. Such control rooms use filtration and air-conditioning systems to meet heat and cleanliness requirements. Tests on filter elements have shown that they prevent the passage of carbon fibers (i.e., transfer functions less than 10^{-5} (refs. 25 and 42)). Municipal incinerators must contend with explosive dust; therefore, their electrical installations are sealed and are essentially invulnerable to carbon fibers.

For utilities, airborne carbon fibers can be expected to cause some failures in older telephone exchanges and within the general purpose type items which support operations. The principal economic impact would be the costs associated with troubleshooting and repair.

Commercial Facilities

Some commercial institutions (such as banks and insurance companies) depend critically upon data stored in central computers. A failure which disturbed such records would constitute a major economic loss. To carry away the heat generated by the equipment and to provide the isolation needed for efficient operation, the central units of such computers are housed in special, independently ventilated and air-conditioned rooms. These measures appear sufficient to protect critical records against errors or other damage by carbon fibers. The other equipment in commercial installations is not protected to the same degree. Carbon fibers which enter commercial buildings through doors or ventilation systems can find their way into items such as cash registers, calculators, and point-of-sale terminals. These items have been tested for vulnerability (ref. 50).

Radio and television stations utilize a substantial amount of electronic equipment mounted in relatively open cabinets. Airborne fibers entering a control room or a

transmitter site can cause electrical failures of individual units. However, most studios install their equipment in a number of small rooms isolated from each other; thus, the total shutdown of a station would require a number of nearly simultaneous failures.

Generally, exposure to airborne carbon fibers could result in a number of failures within items of working equipment in commercial facilities. In some cases, spare units may be available. The economic impact becomes the cost of troubleshooting and repair plus any costs associated with substituting the spare and with the disruption of the service provided by that piece of equipment.

Manufacturing Plants

The selection of a representative cross section of manufacturing facilities was guided by statistics from the Bureau of the Census and utilized their Standard Industrial Classification (SIC). The 21 manufacturing plants surveyed are typical of facilities which produce 85 percent of the total value of shipments attributed to the U.S. domestic industry. All depended upon electrical or electronic equipment. In four classes of operations, electrical failures could have a major economic impact. In a continuous-process type of production (e.g., papermaking and textile fiber spinning), failure of a control system could spoil some of the product and then require overtime premiums to regain the production lost. In an assembly line, a failure could idle a work force and impose a loss of production. In an automated production line, a failure could idle a work force, spoil some of the product in the line, and incur substantial costs during the recovery of production. In the manufacture of electronic or electrical equipment, carbon fibers could damage production equipment and perhaps leave latent failures within the delivered product.

Protective measures now employed to guard against failures attributable to particular environmental concerns also minimize or prevent failures from airborne carbon fibers. For example, many control system elements for the continuous-process industries operate in corrosive environments of pulp mills and chemical plants. The protection (coated circuit boards, sealed cases, etc.) used on controls operating in corrosive fumes also protects against airborne carbon fibers (ref. 25). Critical assembly lines are continuously monitored for breakdown or bottlenecks; a problem receives immediate attention to minimize the interruption of services. Wherever an assembly line must utilize failure-prone equipment, spare or backup units are available. Numerically controlled machine tools are major users of electronics in automated production lines. Here, the environment of cutting lubricants and machining debris dictate the use of sealed or well-filtered enclosures. The manufacturers of electronic equipment employ "clean rooms" to provide cleanliness during the critical steps of populating circuit boards, soldering leads, and final assembly. The air-conditioning and filters used in these rooms also provide protection from airborne carbon fibers. These patterns of protection extend

into other industries. For instance, many rooms of food processing plants are routinely washed down to maintain high standards of sanitation and cleanliness. Electronic weighing devices are protected against such washings and, consequently, against carbon fibers. Mass production industries, machine shops, and printing plants usually must control temperature, dust, or humidity to achieve the environmental conditions conducive to good quality in their products.

The installation of industrial electrical circuitry is governed by wiring codes formulated by the National Electric Manufacturers Association (NEMA). They define twelve classes of wiring enclosures for industrial applications. Of these, only three permit openings which admit as many as 1 percent of carbon fibers present in the surrounding area (ref. 25). Thus, industrial electrical equipment receives substantial protection against carbon fibers through use of standard electrical enclosures.

Facility Classification

The foregoing data and observations were used to characterize the features of industrial installations throughout the country. The characterizations were made for each of a large number of generic categories listed in the Standard Industrial Classification (SIC), prepared by the Bureau of Census. Each category was described by building type, ventilation scheme, unique internal environment, vulnerability of equipment, and qualitative impact of a failure. These data become the basis for the economic evaluations described in the next section.

RISK ASSESSMENT

Computations

The risk assessment involved computation of the possible economic impact of damage to electrical and electronic equipment caused by released carbon fibers. As discussed in previous sections, the probability of shock hazards was extremely remote and no health hazards from carbon fibers had been identified. Therefore, no further consideration was given in the risk assessment to the possibility of human injury or death. Further, since analyses and tests have shown that only single fibers longer than 1 millimeter contribute significantly to electrical and electronic failures, the risk computations were limited to the calculation of the economic consequences of electrical failures caused by release of single carbon fibers longer than 1 millimeter.

Two contractors – ORI, Inc., and Arthur D. Little, Inc. (ADL) – were chosen to assemble and supplement data developed under NASA auspices as described in the preceding sections of this report and to independently develop methods and make risk computations. Both contractors analyzed the risks associated with the use of carbon fibers in

commercial transport aircraft (refs. 60 and 61) and assessed the extent of carbon-fiber-induced outages in power distribution systems (refs. 61 and 62). ADL also analyzed the risk associated with the use of carbon fibers in general aviation aircraft (ref. 63).

Carbon fiber risk from commercial transport aircraft accidents.- In computing the risk associated with the use of carbon fibers in commercial aircraft, many thousands of aircraft accidents were simulated. Each accident was characterized by numerous variables. The contractors made extensive use of statistical techniques in the simulations and associated analyses. They used similar computational methods; however, their choice and treatment of the variables differed as did their synthesis of the results of the individual accident simulations into national risk profiles. Tables IV and V outline the computational steps and the variables used by the contractors in performing the carbon fiber risk computations for commercial aircraft.

Individual accidents were simulated by random selections of a number of variables associated with the accident location, the operational mode, the type of aircraft, the extent to which carbon fibers were involved, and whether or not explosion occurred. The values of the variables and their distribution were based on detailed analysis of National Transportation Safety Board records and records of jet aircraft accidents in which fires were involved (refs. 7 and 8). The projected mix of aircraft in the fleet for the target year of 1993, the extent of carbon fiber usage in the fleet, the fraction affected by fire, and the fraction of available carbon fiber released as single fibers over 1 millimeter long were established in accordance with data presented in the "Fiber Source" section of this report. The behavior of the fire plume that carries the released fibers aloft and the downwind transport and diffusion processes were modeled (refs. 64 and 65) using established methods discussed in the "Fiber Transport" section of this report. The necessary meteorological inputs for these calculations were drawn at random from local weather statistics for each of the airports for which the calculations were made.

The transport and diffusion calculations provided the fiber exposures or dosages up to 80 kilometers downwind of the simulated accident. The downwind areas were subdivided into sectors. The distributions of businesses, industries, public facilities, and private residences within these sectors were then determined from county-based economic and census data. Categories were established which grouped similar types of facilities. Building types and equipment complements were assigned according to data gathered during the facility surveys discussed in an earlier section of this report. Building types were characterized by ventilation parameters obtained from standard engineering sources and modified by particular experimental data appropriate to the carbon fibers. These parameters were used to calculate the transfer function, or the fraction of the fibers outside each building that would enter. The risk assessment model thus determined the exposure or dosage to which vulnerable equipment was subjected. Mean

TABLE IV.- ADL RISK COMPUTATION

Parameter	How established
Airport	Select one of 26 airports
Size of aircraft	Random selection of small, medium, large from fleet mix for airport
Composite mass per aircraft	Random selection from a distribution for each aircraft size
Percent of composite involved	Estimate from accident statistics and where carbon fiber is used in structure
Phase of operation	Random selection of take-off, landing, or other from accident statistics
Likelihood of explosion	Random selection of 0 or 1 from statistics for each phase, Mean = 5.4 percent
Percent of fiber released[a]	1 percent for 94.6 percent fire-only accidents or 3.5 percent for 5.4 percent fire-plus-explosion accidents
Radial distance from airport center	Random selection of 0, 1, 10 km from accident statistics
Azimuth from airport center	Random selection of 0° to 360° from runway angle and usage statistics
Wind velocity	Random selection from local weather statistics
Wind direction	Random selection from local weather statistics
Temperature	Random selection from local weather statistics
Pasquill stability class	Random selection from 1 to 6 from weather statistics
Quantity of fuel carried	Fixed by type of aircraft, phase of operation
Quantity of fuel burned	Random selection, 0 to 100 percent, from accident statistics
Duration of fire	Random selection, 2 to 35 min, from accident statistics and quantity of fuel burned
Plume width at equilibrium altitude	Calculate from fire dynamics and stability class
Virtual point source of fibers:	
Fire only	Calculate from plume width at equilibrium altitude
Explosion	Ground level
E-distributions	From plume, transport equations, wind direction calculated for 8 octants, 5 radial bands, and 50 points within each such sector downwind
Facility demography	From county census data for 15 SIC categories for same radial-octal points as above
Transfer function	By SIC categories, season, filters, seals, etc.
Vulnerability $\bar{E}$	For 153 equipment types in 15 facility categories
Cost of failures, repair	5 severities, for each of 15 SIC categories, \$80 to \$2500
Cost of failures, disruption	3 severities, value depends on size of facility
Cost per accident	Calculate from foregoing
Costs for many accidents at airport	Calculate from foregoing
Single-accident cost profile for airport	Calculate from foregoing
Costs for 25 other airports	Calculate from foregoing
Single-accident cost profile for nation	Calculate from airport profiles weighted by airport share of national operations considering weather factors
National annual risk profile	Calculate from foregoing via random selection of accidents per year from Poisson distribution with Mean = 2.7

[a]3.5 percent was used, not 2.5 percent as reported in reference 60.

TABLE V.- ORI RISK COMPUTATION

Parameter	How established
Size of aircraft	Small, medium, or large per fleet mix — Joint random selection
Airport	1 of 9 airports per usage by aircraft sizes — Joint random selection
Accidents per year with fire and carbon fiber	0 or 1 per airport from Poisson distribution with Mean = 2.6 per year — Joint random selection
Amount of carbon fiber involved	Random selection, 0 to 469 kg, depends on 19 aircraft types, 2 operational phases, 2 severities of damage
Amount of carbon fiber released	1 percent for fire only in 97 percent of accidents, 3.5 percent for explosions in 3 percent of accidents
Plume height	Calculate from fuel carried for each aircraft size, 3 operational phases, 2 severities, limit by inversion altitude
Wind speed	Joint random selection from local weather statistics
Wind direction	Joint random selection from local weather statistics
Pasquill stability	Joint random selection from local weather statistics
Exposure E	Calculate for 5 points in each county up to 80 km away
Transfer functions	Mean values for 7 categories of buildings
Vulnerability $\overline{E}$	Assign by 15 equipment types in 20 SIC categories per county
Complete failures of industries	Random selection from $E/\overline{E}$ per SIC categories (primary power)
Partial failures of industries	Random selection from $E/\overline{E}$ per SIC categories (internal)
Cost per accident	Calculate from expected values of repair, lost time, and product: For industry, by counties and SIC categories, number of employees, payroll, and share of GDP For households, by county census, \$50 per TV, \$100 per hi-fi failed For avionics, by aircraft at gate or maintenance docks, considering day-night, 15 vulnerable equipment categories, ventilation factors for each
Costs for 2500 accidents	
Costs for 8 other airports	
National risk profile	Random selection from airport cost distributions, number of selections for yearly set from Poisson distribution with Mean = 2.6 accidents per year

exposure to failure $\overline{E}$ for equipment and equipment combinations were established based on data discussed in the "Vulnerability of Equipment and Shock Hazard" section of this report. From the calculated interior exposures, either a likely number of failures (ORI) or the probability of failure (ADL) was computed for specific classes of vulnerable equipment in each type of business, industry, and public facility. Impact on households was assessed by computing the expected cost and probability of failure. The repair cost for damaged business, industrial, and public facility equipment was estimated for generic classes of equipment. Impact on facility operations was assessed as either the loss of one day's share of gross domestic product (ORI) or an expected-value loss based on

economic analysis of typical facilities visited during facility surveys (ADL). The vulnerability of avionics equipment aboard aircraft parked at an airport was included in the above computation. The number of aircraft in a potentially vulnerable state at each of the airports was determined from data provided by the aircraft manufacturers (refs. 53, 54, and 55).

From the foregoing costs of failures in industries, businesses, public facilities, households, and parked aircraft, the models generated an estimate of the total economic impact of one accident. This process was repeated until a sufficient number of accidents had been simulated to establish a stable distribution of individual accident costs for an airport.

ORI selected nine major airports as representative of all U.S. airports handling commercial jet operations. They distributed the number of accidents occurring in a year (determined from a Poisson distribution) to these airports in proportion to their prorated share of U.S. operations. Costs were summed for individual years and the process was repeated until a stable distribution of yearly costs was obtained. The ORI national annual risk profile was developed from this distribution.

ADL selected 26 airports to represent all U.S. airports having commercial jet operations. From the individual accident distributions for the separate airports, they developed a national distribution for costs of one accident. They then drew from this distribution to obtain the costs of yearly sets of accidents, from which a national annual distribution and a risk profile were developed.

Carbon fiber risk from general aviation aircraft accidents.- The use of the foregoing procedures to analyze risk from general aviation accidents would have required a prohibitive effort because these accidents occur with much greater frequency and at much more widely scattered points. On the other hand, much smaller quantities of carbon fiber are likely to be released and, therefore, a much smaller risk is involved in a given accident.

Accordingly, ADL developed a simplified analytic approach (ref. 63) that employed expected values for many of the input data as follows:

- The size of the 1993 fleet of general aviation aircraft and the number that would carry carbon fiber composites were estimated. For three classes of aircraft, the expected mass of such composites per aircraft was computed: for single-engine airplanes, 7.0 kilograms; for twin-engine and jet-engine airplanes, 20.5 kilograms; and for rotary-wing and unpowered aircraft, 50.5 kilograms.

- The mass of fiber that was expected to be released from each of these three categories of aircraft was taken to be 2.9 percent of the fiber carried in fire accidents that led to total destruction and 0.76 percent in accidents with substantial damage of the airframe.
- The fibers released were assumed to be uniformly distributed over the county in which any accident occurred.
- Of the 354 general aviation accidents expected per year, 88 were expected to involve carbon fibers and fire, and these were allocated to 3000 counties in the United States according to each county's share of the total operations.
- The potentially vulnerable industrial, business, and household equipment was cataloged into 81 categories for each of the 3000 counties. Appropriate filter factors and vulnerabilities were assigned to the 81 categories.

The quantities thus defined were statistically combined and appropriate weighting factors applied to establish a mean number of equipment failures per accident. Failures were expected to occur in proportion to $E/\overline{E}$, as discussed in the section on vulnerability. Because very small masses of fibers were expected to be released in any accident, the mean number of failures per accident was only 0.022. About 98 percent of all accidents were not expected to cause any failures.

A cost was assigned to each failure depending on the cost of repair and the impact on industrial operations, if applicable. These costs were transformed to mean costs per failure by taking a weighted average for the 81 equipment categories and the likelihood of occurrence for each failure. Because the overwhelming majority of failures are expected to occur in readily repaired industrial and household equipment, the expected cost per failure was small, \$131.

The product of 0.022 (failures per accident) and \$131 (cost per failure) yielded a mean cost of only \$2.88 per accident. The mean national risk was taken to be 88 (the expected number of accidents) times \$2.88, or \$253 per year. Because the number of accidents per year and the number of failures per accident are appropriately assumed to be random variables with Poisson distributions, their means also determine their variance. From this, the standard deviation of annual national risk was computed to be \$1067.

Although this simplified method provides estimates of the expected loss and its variability, it does not adequately define the distribution of costs, particularly for the rarely occurring, but possible, high-cost incidents. However, upper bounds were computed for the probability of occurrence of the high-cost accidents.

To provide a comparison of predictions by this method with predictions made in other ways, ADL used the same method to analyze the transport aircraft risk described earlier.

Analysis Results

The national annual carbon fiber risk profiles developed by ORI and ADL from the commercial aircraft accident simulations are shown in figure 32. Mean annual damage

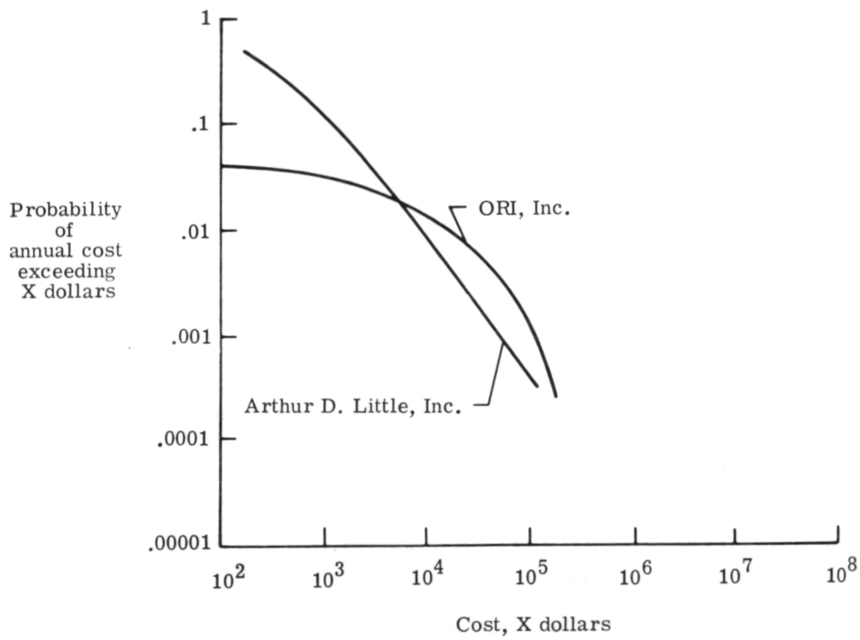


Figure 32.- 1993 national risk profile for carbon fiber released from commercial aircraft accidents. 1976 dollars; 1993 carbon fiber usage assumed.

estimates of approximately $470 were calculated by both ORI and ADL; however, the ORI estimate had a somewhat higher standard deviation. The costliest accidents were $178 000 in the ORI simulation and $74 000 in the ADL simulation. Both studies found that damage was sustained principally by business and industry. Household damage contributed about a third of the costs in a typical ADL accident simulation and averaged less than 3 percent in the ORI simulations. Avionics costs were extremely small.

The ADL simplified analysis of commercial aircraft crash fires predicted a mean annual damage of $1220. This analysis also indicated a slightly higher probability of high-cost accidents.

The probability of failure of avionics in other aircraft in the vicinity of an accident was analyzed separately by the aircraft manufacturers (refs. 53, 54, and 55). The expected number of avionic equipment failures due to carbon composite crash fires was found to be on the order of 0.0003 percent of the current normal operational failure rate. No situations were identified in which the safety of the aircraft was affected.

The sensitivity of the risk from commercial aircraft accidents to variations in input parameters was analyzed. Table VI shows the effect of five changes on mean damage and standard deviations. The effects on the risk profile, in most instances, are roughly equal to the change in input parameters.

TABLE VI.- COST SENSITIVITY

Change to input	Mean damage changed by factor of -	Standard deviation changed by factor of -
Released carbon fibers doubled	2	2
Accident rate doubled	2	1.7
All aircraft have 10 954 kg of carbon fiber (7 times average)	7	4.5
Explosions with all fires (3.5 times fire-only fiber release)	3	2
Weather always stable (Class E)	1.5	1.2

Both ADL and ORI calculated confidence bounds for their risk profiles as they are affected by the number of simulations. Both showed that, with 95 percent confidence, the risk profiles reflect costs to within a factor of two of what an infinite number of simulations would provide. A judgment on the overall confidence limits is difficult to establish because whenever doubt existed regarding a parameter, a conservative value was used in the analysis. Therefore, the profiles should represent upper bounds on the 1993 risk. Reference 66 contains an independent investigation of various statistical aspects of carbon fiber risk assessment modeling.

The ADL analysis of general aviation crash fires in 1993 indicates that the mean damage from carbon fiber was \$253 annually with only one chance in 10 000 of exceeding \$110 000 in damage (ref. 63).

Both ORI and ADL made separate analyses of possible power outages resulting from carbon fiber releases. Their work was based on vulnerability of high-voltage electrical

insulation developed by the Department of Energy and reported in reference 3. The ADL analysis (ref. 62) was based on the area coverage equation for exposure (ref. 35) to estimate the maximum number of insulators which could fail during any release. This resulted in an upper bound estimate that 0.7 customers per year would be affected by a power outage. The ORI analysis (ref. 61) assumed that all U.S. jet transport accidents occurred at Los Angeles, that all were worst-case accidents, and that the wind always blew the cloud toward the most critical area. This calculation showed that 23 customers per year would be affected by a power outage, or one carbon-fiber-induced outage would occur for every 200 000 to 1 000 000 that occur for other reasons.

Some of the airborne debris from composite fires was in single-lamina strips. These strips can fall across power line parts and cause momentary arcs. An analysis of the expected distribution of such strips (ref. 2) showed that 1-meter-long strips could have deposition densities as high as 0.5 strip/m^2 within the first few hundred meters downwind of a crash. The probability that such a strip would land on a power line pair spaced 0.6 meter apart was calculated to be 1 in 1000 in an accident involving 10 000 kilograms of composites (ref. 58). Thus, the risk to the power distribution network from carbon composite lamina strips is insignificant.

Discussion of Results

The carbon composites used in all of the tests are examples of the type that are currently or contemplated to be in use in civil and military aircraft. Improvements could result in products that, when burned, release either a larger or smaller amount of carbon fiber or result in a carbon fiber that is more or less damaging to electrical or electronic equipment. However, because several years of evaluation are required to certify a new material for aircraft applications, any new material is unlikely to receive more than token acceptance by 1993, the year chosen as the focus for this study.

Basing the vulnerability of equipment on the current practice in electrical and electronic equipment ignores a technology trend that will provide a very substantial reduction in equipment vulnerability. Several factors are expected to affect vulnerability: the increased use of coated circuit boards and integrated circuits, the reduced power requirements of solid-state electronics, and the recent aircraft practice of totally enclosing or filtering and air-conditioning electronics. All reduce the potential damage that carbon fibers can cause. The stimulus for each of these practices is the need for highly reliable low-cost electronic systems. One factor that may not have been fully evaluated was the potential growth, in the next 15 years, in the numbers and types of potentially vulnerable equipment. However, this factor is expected to be outweighed by the trend to improve equipment.

The analysis assumed that carbon fiber debris at the accident site is cleaned up. (This is the current standard practice for military aircraft crashes.) The test results show that most of the fire-damaged carbon composite remains on the ground at the accident site as charred and partially oxidized carbon fiber held together by products of combustion. The amount of debris remaining was found to be many times that lofted into the air by the fire. This debris represents a potential delayed source of airborne carbon fiber and therefore should be removed. Care should be taken to prevent agitation of this debris before and during the cleanup. Fiber "hold-down" chemicals, such as polyacrylic acid (PAA), are being developed to prevent the spread of free fibers from crash sites. When sprayed on carbon composite debris, the chemical coats the carbon fibers and prevents them from being released upon handling of the fire debris. The additional cost of the cleanup and the preventive treatment of the debris (minor by comparison to the total cost of an accident) was not taken into account in the estimate of the public risk.

The predicted damage from release of carbon fibers during burning of composite structures should be judged acceptable or unacceptable by comparison with other risks or benefits associated with the ultimate use. Two measures may reasonably be chosen for comparison: the benefit associated with carbon fiber application and the cost of the accidents.

The benefit obtained in the application of carbon composites to commercial aircraft is well recognized. The manufacturer of one aircraft under construction estimates that the use of only 400 kilograms of carbon fiber in the structure results in a reduction of 400 kilograms of fuel used per day. The fuel savings over the life of the aircraft is very significant.

The total costs of 155 air transport accidents occurring between 1966 and 1975 have been studied by the Federal Aviation Administration (ref. 67) and by one of the contractors performing the risk computations (ref. 61). Accident cost (in 1974 dollars) ranged from less than 1 million dollars to nearly 50 million dollars per aircraft (non-fire accidents were included). The mean cost of those accidents, where the aircraft sustained at least substantial damage, ranged from 5 million dollars for small jet aircraft to in excess of 10 million dollars for large jet aircraft. Considering the number of aircraft crashes, the potential damage from released carbon fiber must be compared with annual aircraft crash costs of nearly 100 million dollars. Relative to such costs even the $178 000, worst-case incident simulated (having a probability of occurrence of once in 34 000 years) is a low-cost event.

CONCLUSIONS

A comprehensive assessment of the possible damage to electrical and electronic equipment caused by accidental release of carbon fibers from burning civil aircraft with carbon composite parts has been completed. The study concluded that the amount of fiber likely to be released is much lower than initially predicted. Carbon fiber released from an aircraft crash fire was found (from atmospheric dissemination models) to disperse over a much larger area than originally estimated, with correspondingly lower fiber concentrations. Long-term redissemination of fiber was shown to be insignificant if reasonable care is exercised in accident cleanup. The vulnerability of electrical equipment to structural fibers in current use was low. Consumer appliances, industrial electronics, and avionics were essentially invulnerable to carbon fibers. Shock hazards (and thus potential injury or death) were found to be extremely unlikely.

The overall costs were shown to be extremely low in 1993, the year chosen as a focus of the study. The expected annual cost was shown to be less than $1000 with only one chance in 2000 of exceeding $150 000 loss annually. For comparison, the costs of air transport aircraft accidents occurring between 1966 and 1975 range from less than 1 million dollars to nearly 50 million dollars per accident (non-fire accidents are included). The mean cost of those accidents, where the aircraft sustained at least substantial damage, was about 6 million dollars. Thus, even the worst-case carbon fiber incident simulated is relatively low cost.

The following conclusions are drawn from these results:

- The risk of electrical or electronic failures due to carbon fibers should not prevent exploitation of carbon composites in aircraft.
- Additional protection of aircraft avionics to guard against carbon fibers is unnecessary.
- A program to develop alternate materials specifically to overcome the potential electrical hazard is not justified.

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